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MIST-FLOW HEAT TRANSFER USING SINGLE-PHASE VARIABLE-PROPERTY APPROACH

by Yih-Yun Hsu, Glenn R. Cowgill, and Robert C. Hendricks

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ERRATA

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THERMODYNAMIC PROPERTIES OF POTASSIUM TO 2100° K

By Sheldon Heimel

September 1967

Page 13: The reference number in line 17 should be 8.

Page 13: The reference number in line 18 should be 7.

Page 16: The equation number in line 13 should be (7).

Page 21: The equation in line 6 should read

$$\left(\Delta H^{o}_{298}\right)_{v} = \left(H^{o}_{298}\right)_{monomer} - \left(H^{o}_{298}\right)_{c} = \left(H^{o}_{298}\right)_{monomer}$$

Page 21: The equation in line 8 should read

$$\left(H^{o}_{T}\right)_{monomer} = \left(H^{o}_{T} - H^{o}_{298}\right)_{monomer} + \left(\Delta H^{o}_{298}\right)_{v}$$

Page 24: In the key in figure 4 the first item should read "Experimental data (ref. 9)."

Page 28: In line 22 of the right column the definition of H_T should read "enthalpy of real gas at T^{o} K."

Page 29: In line 22 of the right column the units for $\left(\Delta S^{o}_{T}\right)_{v}$ should read "cal/(mole)(^{o}K); J/(mole)(^{o}K)."

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SUMMARY

Film-boiling mist flow is treated as a single-phase flow with properties being synthesized from those of liquid and vapor phases weighted according to their respective volume fraction. Such a synthesizing approach renders it possible to apply the technique for single-phase turbulent flow to the two-phase flow. Computational results for film-boiling hydrogen at low pressure predicts the experimental data within 25 percent; the deviation between the analytical and experimental results increases gradually with increasing pressure. Further analysis showed that the deviation was due to the assumptions of a thermodynamic equilibrium and homogeneous distribution of void. A simplified design method is proposed so that the heat-transfer coefficient can be calculated from the Dittus-Boelter equation by specifying a reference temperature and a reference void fraction for computation of properties. The coefficient for determining such a reference temperature and void is primarily a function of the bulk void fraction.

INTRODUCTION

In the aerospace and nuclear engineering fields, two-phase flow problems are frequently encountered. Among these, the problem of film-boiling two-phase flow is of particular importance to regenerative cooling of a rocket engine. This phenomenon occurs in the cooling passage where the wall temperature is usually several hundred degrees above the boiling point of the liquid coolant.

Numerous efforts have been directed toward the study of film-boiling two-phase flow. Most of these efforts were concerned with the accumulation of data to correlate a function of heat-transfer coefficient with a function of flow conditions. However, only limited effort has been applied to the theoretical aspects of the problem. In order that present knowledge of single-phase turbulent flow can be transferred to two-phase flow, this report proposes a model in which the film-boiling mist flow is treated as a single-phase flow of a fluid with variable properties. The variable properties are synthesized from the liquid and gaseous properties weighted according to their respective volume fractions (i. e., void and holdup).

In the following sections, this model using the variable-property approach will be postulated, and the computed values of heat flux for a given wall temperature and flow condition at a pressure of approximately 50 psia (34.5 N/cm^2) for boiling hydrogen flowing upward in a vertical tube will be compared with existing experimental data. For design purposes, a simplified scheme will also be proposed to provide the reference temperature and void for evaluating a set of film properties so that the conventional Dittus-Boelter equation can be used. Finally, some results of the analysis at higher pressures (up to 170 psia; 117 N/cm^2) will be discussed.

Film-boiling two-phase flow has been studied experimentally by many researchers (e.g., refs. 1 to 5). References 1 and 2 present empirical correlations of heat-transfer coefficient as function of a parameter χ_{tt}, which is similar to that used in correlating two-phase pressure drop (refs. 6 and 7). References 3 and 4 give the description of flow patterns in film-boiling flow. In general, the flow pattern becomes mist when the void is high. In reference 8, the existence of a so-called "dry-wall mist-flow" regime was noted in two-phase flow when the wall temperature and quality are high.

As to the analytical studies of two-phase flow, both Bankoff (ref. 9) and Levy (ref. 10) used a single-phase variable property approach with satisfactory results. Bankoff's analysis was limited to bubbly flow; Levy's analysis was based on a mixing length concept, but was also only applicable to the wetted wall. Unfortunately, neither of these excellent analyses could be extended to film-boiling conditions. Topper (ref. 11) also briefly discussed flow behavior in the mist-flow regime. More recent contributions to the film-boiling two-phase flow are made by references 4 and 5.

One of the important reports on turbulent flow with variable properties, is that of Deissler (ref. 12), in which an expression for eddy diffusivity was proposed that takes into account both the velocity profile and the physical properties. Deissler's approach is versatile and, therefore, applicable to many problems that involve fluids with variable properties. Later, for the benefit of design engineers, Deissler and Presler (ref. 13) recommended a simplified method for predicting heat-transfer coefficient that makes use of a reference temperature for evaluating properties.

ANALYSIS

In this study, a mist-flow pattern is considered. The velocity and temperature profiles are assumed to be fully developed. The flow is primarily vapor (in volumetric fraction), with small droplets dispersed in it and diffusing toward the wall. The true flow is assumed to be equivalent to the flow of a single-phase fluid with spatially varying properties, the properties being evaluated from a combination of liquid and vapor phase properties weighted according to the volumetric fraction. Then Deissler's approach is used to treat this variable-properties problem. A more detailed description of the model is listed in the following sections.

Basic Assumptions

(1) The velocity and temperature profiles are assumed to be fully developed. Specifically, acceleration is assumed to have no effect on these local profiles.

(2) Convective terms and viscous dissipation terms are neglected from the momentum and energy equations.

(3) Deissler's expression for eddy diffusivities is used.

(4) The turbulent Prandtl number ϵ_m/ϵ_t is assumed to be one so that both eddy diffusivities are denoted by ϵ. (Symbols are defined in appendix A.)

(5) The properties, ρ, C_p, K, and μ, are synthesized by the following technique:

$$\varphi = \alpha_l \varphi_l(T_{sat}) + \alpha_v \varphi_v(T) \tag{1}$$

where φ represents the synthesized property; $\varphi_l(T_{sat})$ is the liquid property at saturation temperature and $\varphi_v(T)$ is the vapor property at the local temperature.

(6) The void distribution profile is assumed to be

$$\alpha_l = 0$$

$$\alpha_v = 1$$

for $T > T_{sat}$, that is, in the superheated vapor film, and

$$\frac{\alpha_l}{\alpha_{l,CL}} = \frac{u}{u_{CL}} = \frac{u^+(y^+)}{u^+(r^+)} \tag{2}$$

when the saturation temperature is reached.

(7) The droplets are assumed to be so small that the relative velocity of droplets with respect to the vapor velocity is negligible compared with the local axial velocity, but may not be negligible when compared with the velocity fluctuation in the radial direction. This assumption implies that:

(a) The relation between void and quality is simplified by neglecting the local slip velocity.

(b) The droplets, having higher density, would retain their momentum in the transverse direction without damping when flowing near the wall; whereas, a vapor eddy would be damped out as the distance from wall diminishes. Thus, liquid droplets will be assumed to diffuse from the bulk region into the wall region with a diffusivity represented by the value of ϵ at the edge of the wall region. These drops impinge on the wall and are evaporated. Since these droplets are few in number and their time of travel through the superheated vapor in the wall region is short, they do not affect the velocity and temperature profiles in the superheated vapor film. The presence of droplets would affect the profiles in the saturated core region, however.

Basic Equations

Quality and void. - The quality and the mass flow rate can be expressed in terms of void distribution as

$$x = \frac{1}{\dot{w}} \int_0^r \alpha_v \rho_g u 2\pi(r - y)dy \tag{3}$$

$$\dot{w} = \int_0^r (\alpha_v \rho_v + \alpha_l \rho_l) u 2\pi(r - y)dy \tag{4}$$

If the velocity profile is almost flat in the turbulent core and the laminar part of boundary layer is very thin, the average quality and void can be expressed in simplified forms as

$$x \cong \frac{\overline{u\rho_v \alpha_v}}{\overline{\rho u}} \approx \frac{\rho_{v,sat}\bar{\alpha}_v}{\frac{\overline{\rho u}}{\bar{u}}} = \frac{\rho_{v,sat}\bar{\alpha}_v}{\rho_{v,sat}\bar{\alpha}_v + \bar{\alpha}_l \rho_l} \tag{3a}$$

where

$$\rho = \alpha_v \rho_v + \alpha_l \rho_l$$

$$\bar{\alpha}_v = \frac{\frac{x}{\rho_{v,sat}}}{\frac{x}{\rho_{v,sat}} + \frac{(1 - x)}{\rho_l}} \tag{4a}$$

Void distribution. - It is assumed that the liquid concentration profile is analogous to the velocity profile; that is,

$$\frac{\alpha_l}{\bar{\alpha}_l} = \frac{1 - \alpha_v}{1 - \bar{\alpha}_v} = \frac{u}{u_b} \tag{5}$$

or

$$\frac{\alpha_l}{\alpha_{l,CL}} = \frac{1 - \alpha_v}{1 - \alpha_{v,CL}} = \frac{u^+}{u^+_{CL}} \tag{5a}$$

Enthalpy. - The enthalpy of the two-phase fluid per unit volume is

$$\rho H = H_l \alpha_l \rho_l + H_v \alpha_v \rho_v$$

If the datum for enthalpy is set equal to that of the saturated liquid

$$H_l = 0$$

then

$$H_v = \lambda + \int_{T_{sat}}^{T} C_{p,v}\, dT \tag{6}$$

or

$$\rho H = \left(\lambda + \int_{T_{sat}}^{T} C_{p,v}\, dT\right)\alpha_v \rho_v \tag{7}$$

Shear-stress equation. - The shear stress can be expressed, following reference 12, as

$$\tau = (\mu_v + \epsilon\rho)\frac{\partial u}{\partial y} \tag{8}$$

Heat flux equation. - The heat is transferred through conduction and diffusion of enthalpy. In analogy to equation (8),

$$-q = k\frac{\partial T}{\partial y} + \epsilon\rho\frac{\partial H}{\partial y} \tag{9}$$

From equation (7), the term $\epsilon\rho(\partial H/\partial y)$ can be expanded into

$$\epsilon\rho \frac{\partial H}{\partial y} = \epsilon\alpha_v\rho_v \frac{\partial H_v}{\partial y} + \epsilon\rho_v H_v \frac{\rho_l}{\rho} \frac{\partial \alpha_v}{\partial y} + \epsilon\alpha_v\alpha_l H_v \frac{\rho_l}{\rho} \frac{\partial \rho_v}{\partial y} \tag{9a}$$

But the last term in equation (9a) vanishes when $\alpha_l \to 0$ (close to the wall) or when $(\partial\rho_v/\partial y) = 0$ $(\rho_v = \rho_{v,\,sat}$ in the two-phase core). Thus,

$$\epsilon\rho = \epsilon\alpha_v\rho_v \frac{\partial H_v}{\partial y} + \epsilon\rho_v H_v \frac{\rho_l}{\rho} \frac{\partial \alpha_v}{\partial y} \tag{9b}$$

The heat flux can also be split into two parts

$$-q = -q_c + (-q_h) \tag{9c}$$

when

$$-q_c = k \frac{\partial T}{\partial y} + \epsilon\alpha_v\rho_v C_{p,\,v} \frac{\partial T}{\partial y} \tag{10}$$

is the convective term and

$$-q_h = \epsilon H_v \rho_v \frac{\rho_l}{\rho} \frac{\partial \alpha_v}{\partial y} \tag{11}$$

is the evaporative term.*

Eddy diffusivity. - Deissler's expressions for eddy diffusivity will be used. For the wall region (close-to-wall region)

$$\epsilon^+ = n^2 u^+ y^+ \left(1 - e^{-n^2 u^+ y^+ \nu/\nu_o}\right) \text{ for } \frac{\epsilon}{\nu} \leq 2 \tag{12}$$

For core region (away-from-wall region),

$$\epsilon^+ = \frac{\kappa^2 \left|\frac{du^+}{dy^+}\right|^3}{\left(\frac{d^2u^+}{dy^{+2}}\right)^2} \qquad \text{for } \frac{\epsilon}{\nu} \geq 2 \tag{13}$$

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*It was found through the calculations that, for the range of conditions covered by this report, $q_{h,\,o} << q_{o,\,c}$. Thus, $q_{o,\,c} \approx q_o$ for all practical purposes.

where

$$\epsilon^+ = \frac{\epsilon}{\frac{\mu_o}{\rho_o}} = \frac{\epsilon}{\nu_o} \tag{14}$$

$$u^+ = \frac{u}{\sqrt{\frac{\tau_o}{\rho_o}}} = \frac{u}{u^*} \tag{15}$$

$$y^+ = \frac{y\sqrt{\frac{\tau_o}{\rho_o}}\,\rho_o}{\mu_o} \tag{16}$$

Velocity profile. - A step-by-step integration of the velocity gradient given in equation (8) provides an effective determination of the velocity profile

$$\frac{1}{\tau_o}\frac{du}{dy} = \frac{\frac{\tau}{\tau_o}}{\mu_v + \epsilon\rho}$$

or, in the dimensionless form,

$$\frac{du^+}{dy^+} = \frac{\frac{\tau}{\tau_o}}{\frac{\mu_v}{\mu_o} + \epsilon^+\frac{\rho}{\rho_o}} \tag{17}$$

The present study assumes, by following reference 12, that $\tau/\tau_o = 1$; thus,

$$\frac{du^+}{dy^+} \approx \frac{1}{\frac{\mu_v}{\mu_o} + \epsilon^+\frac{\rho}{\rho_o}} \tag{17a}$$

Temperature profile. - The temperature profile is determined by integrating the temperature gradient given in equation (10)

$$\frac{1}{q_{o,c}}\left(\frac{dT}{dy}\right)_c = \frac{-\dfrac{q_c}{q_{o,c}}}{K + \epsilon\rho_v\alpha_v C_{p,v}} \tag{18}$$

or

$$\frac{dT^+}{dy^+} = \frac{\dfrac{q_c}{q_{o,c}}}{\dfrac{K}{K_o}\dfrac{1}{Pr_o} + \epsilon^+\dfrac{\rho_v}{\rho_o}\alpha_v\dfrac{C_{p,v}}{C_{p,v,o}}} \tag{19}$$

where

$$T^+ = \frac{T_o - T}{\beta T_o} \tag{20}$$

$$\beta = \frac{q_{o,c}\left(\dfrac{\tau_o}{\rho_o}\right)^{1/2}}{C_{p,o}\left(\dfrac{\tau_o}{\rho_o}\right)\rho_o T_o} = \frac{q_{o,c}}{C_{p,o}T_o\rho_o u^*} \tag{21}$$

The present study also assumes, again following reference 12, that $q/q_{o,c} = 1$; thus,

$$\frac{dT^+}{dy^+} \approx \frac{1}{\dfrac{K}{K_o}\dfrac{1}{Pr_o} + \epsilon^+\dfrac{\rho_v}{\rho_o}\alpha_v\dfrac{C_{p,v}}{C_{p,v,o}}} \tag{19a}$$

Note that equations (17) and (19) are coupled, because ϵ is determined by velocity and properties which, in turn, are functions of temperature.

Heat-transfer parameter. - In Deissler's analysis the parameter β is of great importance in determining the heat-transfer coefficient. The physical meaning of β can be shown as follows:

$$\beta_D = \frac{q_o}{C_{p,o}T_o\rho_o u^*} = \frac{\Delta T}{T_o}\,\frac{q_o}{\Delta T K_o}\,d\,\frac{K_o}{C_{p,o}\mu_o}\,\frac{1}{\frac{d u_b\rho_o}{\mu_o}}\,\frac{1}{\sqrt{\frac{\tau_o}{\rho_o u_b^2}}} = \frac{\Delta T}{T_o}\,\frac{Nu_o}{Re_o Pr_o}\,\frac{1}{\sqrt{\frac{f_o}{2}}} = \frac{\Delta T}{T_o}\,\frac{St_o}{\sqrt{\frac{f_o}{2}}} \tag{22}$$

(Note: β_D is the heat-transfer parameter as given in ref. 12.)

where

$$\left.\begin{aligned}
Nu_o &= \frac{hd}{K_o} = \frac{2r^+Pr_o}{T_b^+} \\
Re_o &= \frac{d u_b\rho_o}{\mu_o} = 2r^+u_b^+ \\
Pr_o &= \frac{C_{p,o}\mu_o}{K_o} \\
St_o &= \left(\frac{q_o}{C_{p,o}\rho_o u_b\,\Delta T}\right) = \frac{1}{T_b^+u_b^+} \\
f_o &= \frac{\tau_o}{\left(\frac{\rho_o u_b^2}{2}\right)} = \frac{2}{\left(u_b^+\right)^2}
\end{aligned}\right\} \tag{23}$$

The importance of β can be appreciated by observing that even if $T^+(y^+)$ could be made similar to $u^+(y^+)$, the value of temperature difference $T_o - T$ will vary for any one given dimensionless T^+ depending upon the selection of β. Thus, for each β, a

$Nu = f(Re)$ can be constructed or, alternatively, $Nu = f(\beta, Re)$. Since the β is not known initially, some iterative method has to be used to obtain the proper β. In the case of forced convection without boiling, the value of β could be determined by matching the desired u_b and T_b. But, in the case of boiling two-phase flow, the T_b is the saturation temperature corresponding to the local pressure. Therefore, T_b^+ is not a function of r for the saturated core. As a result, equation (22) alone is insufficient for iteration. Some independent information, such as a friction law or some other expression for β in addition to equation (22) is needed. Such an equation will be provided in the next section by postulating a heat and momentum analogy.

Stanton number and friction factor (analogy between heat and momentum transport). - Dividing equation (10) by equation (8) yields a ratio of heat transport to momentum transport

$$-\frac{q_c}{\tau} = \frac{(K + \epsilon\alpha_v\rho_v C_{p,v})\frac{dT}{dy}}{(\nu_v\rho_v + \epsilon\rho)\frac{du}{dy}} \tag{24}$$

or use the Prandtl number and change the independent variable and equation (24) becomes

$$-\frac{q_c}{\tau} = \frac{\left(\frac{\nu_v\rho_v}{Pr_v} + \epsilon\rho_v\alpha_v\right)C_{p,v}\frac{dT}{dy}}{(\nu_v\rho_v + \epsilon\rho)\frac{du}{dy}} = \frac{\left(\frac{\nu_v\rho_v}{Pr_v} + \epsilon\rho_v\alpha_v\right)}{(\nu_v\rho_v + \epsilon\rho)} C_{p,v}\frac{dT}{du} \tag{24a}$$

Now, by integration of equation (24a) over the wall region where $\epsilon/\nu < 2$, assuming that the coefficient of dT/du can be represented by some mean property (film temperature) and that

$$\frac{q_c}{\tau} = \frac{q_o}{\tau_o}$$

the heat-momentum analogy becomes

$$\frac{q_o}{\tau_o} u_a = \left(\frac{\frac{\nu_v\rho_v}{Pr_v} + \epsilon\rho_v\alpha_v}{\nu_v\rho_v + \epsilon\rho}\right)_f C_{p,v,f}(T_o - T_a) \tag{25}$$

Here, if it is also assumed that, at the edge of the wall region

$$\frac{T_o - T_a}{u_a} \approx \frac{T_o - T_b}{u_b}$$

then

$$\frac{q_o u_b}{\tau_o(\Delta T)C_{p,o}} = \left(\frac{\dfrac{\nu_v \rho_v}{Pr_v} + \epsilon\rho_v \alpha_v}{\nu_v \rho_v + \epsilon\rho}\right)_f \frac{C_{p,v,f}}{C_{p,o}} \tag{26}$$

The left side of equation (26) may be written as

$$\frac{q_o u_b}{(\Delta T)C_{p,o}\tau_o} = \left(\frac{q_o}{(\Delta T)}\frac{d}{K_o}\right)\left(\frac{K_o}{C_{p,o}\mu_o}\right)\frac{1}{\dfrac{\tau_o}{2\left(\dfrac{\rho_o u_b^2}{2}\right)}}\left(\frac{\mu_o}{du_b\rho_o}\right) = \frac{St_o}{\dfrac{f_o}{2}} \tag{26a}$$

Thus, equation (26) becomes

$$\frac{St_o}{\left(\dfrac{f_o}{2}\right)} = \left(\frac{\dfrac{\nu_v \rho_v}{Pr_v} + \epsilon\rho_v \alpha_v}{\nu_v \rho_v + \epsilon\rho}\right)_f \frac{C_{p,v,f}}{C_{p,o}} \tag{27}$$

If it is assumed that the mean value of ϵ/ν between $\epsilon/\nu = 0$ and $\epsilon/\nu = 2$ is $\epsilon/\nu = 1$, then equation (27) becomes

$$\frac{St_o}{\left(\dfrac{f_o}{2}\right)} \approx \left(\frac{\dfrac{\nu_v \rho_v}{Pr_v} + \nu_v \rho_v \alpha_v}{\nu_v \rho_v + \nu_v \rho}\right)_f \frac{C_{p,v,f}}{C_{p,o}} = \left(\frac{\dfrac{1}{Pr_{v,f}} + \alpha_{v,f}}{1 + \dfrac{\rho_f}{\rho_{v,f}}}\right)\left(\frac{C_{p,v,f}}{C_{p,o}}\right) \tag{28}$$

In mist flow, the α_v is usually very close to unity, thus $(\rho_f/\rho_{v,f}) \approx 1$, and (28) may be written

$$\frac{St_o}{\left(\frac{f_o}{2}\right)} \approx \frac{\left(\frac{1}{Pr_{v,f}} + 1\right)}{2} \frac{C_{p,v,f}}{C_{p,o}} \tag{29}$$

Combining equation (22) and (29) yields

$$\beta_A = \left(1 - \frac{T_b}{T_o}\right)\sqrt{\frac{f_o}{2}} \frac{\left(\frac{1}{Pr_{v,f}} + 1\right)}{2} \frac{C_{p,v,f}}{C_{p,o}} \tag{30}$$

(Note: β_A is the expression of heat-transfer parameter as derived from momentum and heat-transfer analogy)

Ratio of transverse velocity to bulk velocity. - In the boiling two-phase flow, evaporation occurs continuously as the flow proceeds down stream. The flow is constantly under acceleration. As evaporation takes place on the wall, expansion of volume occurs, which gives rise to a transverse velocity away from the wall. Such a situation is like that of a blowing boundary layer. In the blowing boundary layer, one important parameter is the ratio of transverse velocity to the free stream velocity, v/u_b (ref. 14). For the boiling two-phase flow, the superficial transverse velocity can be expressed as

$$v = \frac{q_o}{\lambda}\left(\frac{1}{\rho_v} - \frac{1}{\rho_l}\right) \approx \frac{q}{\lambda\rho_v} \tag{31}$$

Thus, the ratio of the two velocities is

$$\frac{v}{u_b} = \frac{q}{\lambda\rho_v u_b} \tag{32}$$

It is interesting to note that the group $q/\lambda\rho_v u_b$ can be considered as a special form of Stanton number $q/\Delta H u_b \rho_v$ if $\Delta H = \lambda$ is used in place of $\Delta H = C_p \Delta T$. Or it can also be shown as a special form of Péclet number as follows: If the energy balance is written as

$$\rho C_p u \frac{\partial T}{\partial x} = -\frac{1}{r}\frac{\partial}{\partial r} rK \frac{\partial T}{\partial r}$$

then the normalization of the variables in the equation yields a dimensionless group $(K/\rho C_p ud)(L/d)$ which is $(1/Pe)(L/d)$. Now, if the energy balance is written as

$$\rho u \frac{\partial H}{\partial x} = -\frac{1}{r}\frac{\partial}{\partial r}(rq)$$

then the normalization process yields a group $(q_0/\rho u(\Delta H))(L/d)$. Comparing the two dimensionless groups shows that

$$\frac{q}{\rho u(\Delta H)} \equiv \frac{1}{Pe}$$

It appears that the choice between Péclet number and the group $q/\rho u(\Delta H)$ depends on the boundary condition. Péclet number will occur for the constant wall temperature case where ΔT is a natural choice for normalization while $q/\rho u(\Delta H)$ will occur for the constant heat flux case where q is used as the normalization factor.

COMPUTATIONAL PROCEDURE

The computations were performed on an IBM 7094-7044 direct-coupled-system. The computer program written in FORTRAN IV language is included in appendix A. It makes use of given flow conditions to compute the Nusselt number.

Iteration is used to determine the correct values of $\alpha_{v,CL}$, r^+ and β. For assumed values of $\alpha_{v,CL}$, r^+, and β the differential equations are numerically integrated until $y^+ \approx r^+$, then $\bar{\alpha}_v$ and $\dot{w}$ are computed. If $\alpha_{v,cal}$ is not equal (within the desired tolerance) to $\bar{\alpha}_{v,w}$, or if $\dot{w}_{cal}$ is not equal (within the desired tolerance) to $\dot{w}_w$, then $\alpha_{v,CL}$ and r^+ are changed as follows:

$$\alpha_{v,CL,new} = \alpha_{v,CL,old} + 0.2(\bar{\alpha}_{v,w} - \bar{\alpha}_{v,cal})$$

$$r^+_{new} = r^+_{old} + r^+_{old} \cdot \dot{w}_{ratio}$$

where

$$\begin{cases} |\dot{w}_{ratio}| < 1 & \dot{w}_{ratio} = \dfrac{\dot{w}_w - \dot{w}_{cal}}{\dot{w}_w} \\ \\ |\dot{w}_{ratio}| \geq 1 & \dot{w}_{ratio} = 0.5\ \mathrm{sgn}(\dot{w}_{ratio}) \end{cases}$$

When $\bar{\alpha}_{v,cal}$ and $\dot{w}_{cal}$ are within the desired tolerances of $\bar{\alpha}_{v,w}$ and $\dot{w}_w$, β_A is computed by equation (30). If β_A and the assumed β are not within the desired tolerance, then the entire iterative procedure is repeated by using this new β. If β_A is within the desired tolerance, final results are computed and output is printed. An outline of the computational procedure is as follows:

(1) Read input, T_o, T_b, P_b, $\dot{w}_w$, u_b, r, x, and $\bar{\alpha}_{v,w}$.

(2) Get wall properties from T_o.

(3) Assume β_A.

(4) Guess u^+_{CL}, r^+, α_{CL}.

(5) Use equations (5a), (12), (13), (17a), and (19a), to get $u^+(y^+)$ and $t^+(y^+)$ curves until $y^+ = r^+$.

(6) Compute $\bar{\alpha}_v$, x, Nu, τ, u*, q, and $\dot{w}$.

(7) If $\bar{\alpha}_v$ does not check with $\bar{\alpha}_{v,w}$, change $\alpha_{v,CL}$, and iterate from step (5) to (7), until $\bar{\alpha}_v \approx \bar{\alpha}_{v,w}$.

(8) If $\dot{w}$ does not check with $\dot{w}_w$, iterate from step (4) to (7) by changing r^+ until $\dot{w} \approx \dot{w}_w$.

(9) After both $\dot{w}_w$ and $\bar{\alpha}_{v,w}$ are obtained, compute β from equation (30), iterate from step (3) to (9) until β is correct.

(10) Print out β, Nu, τ_o, Re_o, q_o, $\dot{w}$, $\bar{\alpha}_v$, and x.

A more detailed description can be found in the block diagram and the program in appendix B.

DISCUSSION OF COMPUTED RESULTS FOR LOW-PRESSURE DATA

Typical runs representing film boiling of hydrogen under various experimental conditions (for pressure below 50 psia (34.5 N/cm^2)) were selected from the data of reference 1. The actual condition of each run was used as input to the computer program to obtain a computed Nusselt number for comparison with the corresponding experimental Nusselt number in reference 1. Computations were performed for experimental conditions with T_0 ranging from 246° to 681° R (137° to 378° K), the equilibrium quality x_{eq} ranging from 0.05 to 0.726, and flow rate ranging from 0.0631 to 0.1772 pound per second (0.0287 to 0.0804 Kg/sec), and the results are tabulated in table I. Plots of typical $u^+(y^+)$ and $T^+(y^+)$ are presented in figure 1. Notice that the T^+ profile is flat in the core region where T^+ is at saturation temperature.

In this work, the analogy between heat and momentum transfer is invoked in the expression for β in terms of q and τ (β_A of eq. (30)) to apply in conjunction with the definition for β (β_D in eq. (22)). This new relation enables the evaluation of β by iteration because the resulting τ and q for an assumed β must satisfy equation (30) if the analogy is correct. In lieu of equation (30), the conventional method for selecting β (ref. 15) would be to iterate against T_b, which, however, is not applicable to the two-phase flow since the temperature profile $T^+(y^+)$ stays flat once the saturation temperature is reached. (See T^+ curve in fig. 1)). A few salient features of the results will be discussed as follows:

(1) The computed and the experimental heat fluxes are plotted against each other in figure 2. Among the runs tested, the predicted heat flux agrees with the experimental value within 30 percent for all except one run, and proffers some confidence in the postulated model.

(2) The model fails for run 1805 (L = 7.4 in., 18.7 cm). The reason for failure is not really known, but is possibly a result of the existence of a different flow pattern. Mist flow might not exist at this low-mass flow rate (0.063 lb/sec; 0.0287 Kg/sec) and low quality (x = 0.159)[1].

(3) The applicability of this program to the entrance region was tested against one experimental case (run 2008, $L/d < 4$). The analytical program failed to predict the experimental result as expected.

(4) In this report, the distribution of droplet concentration α_l (or $1 - \alpha_v$, α_v representing the void) was assumed to be represented by a profile similar to the velocity profile; that is,

$$\frac{\alpha_l}{\alpha_{l,CL}} = \frac{u}{u_{CL}} \tag{5a}$$

In order to evaluate the possible effect of the mist distribution on heat transfer, computations were made on a few selected runs using different mist distributions in the form of

[1]Silvestri (ref. 16) pointed out that there is a lower limit for flow velocity to sustain mist flow. Therefore, if both the flow rate and quality are low, there might not be enough velocity to maintain droplet dispersion. And if there exists in the core large liquid filaments or slugs, the heat-transfer coefficient could be greatly increased.

$$\frac{\alpha_l}{\alpha_{l,CL}} = \left(\frac{y}{r}\right)^{1/m} \tag{5b}$$

where

$$1 < m < \infty$$

The results for $m = 2, 5, 7, 10, 20$, and 1000 are tabulated in table II, showing the ratio q_{cal}/q_{exp} at various m's. The q-ratios, based on an analogy between velocity and droplet-distribution profiles, (eq. (5a)) are listed for comparison. Recall that, usually, for turbulent flow in a tube, the velocity profile can be represented by $7 < m < 10$. From the results in table II, it can be deduced that, in the pressure range of 50 psia, (34.5 N/cm^2) the effect of mist distribution on heat flux is not very strong as long as $m > 2$. Among the various distribution profiles, two of them are of particular interest. The profile represented by equation (5a) implies an analogy between mass and momentum transports, thus having some theoretical justification. The other profile is that of $m \rightarrow \infty$, which is uniform distribution and is simple and easy to use. In the sections to follow, the uniform distribution will be used for simplicity, except when void is assumed to be unity in the superheat vapor film.

(5) The values of β obtained by iterating β_A against β_D are listed in table I. It is interesting to note that β increases with decreasing bulk velocity or increasing heat flux. Since the inverse relation between q_o and u_b also exists in the ratio

$$\frac{v}{u_b} = \frac{q_o}{\lambda \rho_v u_b}$$

A plot is made of β against v/u_b (fig. 3). It appears that some correlation exists between these two parameters.

(6) Also computed are the dimensionless velocity u_a^+ and dimensionless distance y_a^+ where transition from wall region to core region occurs. Again, the product $u_a^+ y_a^+$ appears to be a function of the ratio q/u_b. In reference 14, it was shown that $u_a^+ y_a^+$ is a function of v/u_b for the case of blowing boundary layer. Therefore, the product $u_a^+ y_a^+$ is plotted against the parameter $v/u_b = q/\lambda \rho_v u_b$ in figure 4.

In general, for the case of gaseous forced-convection with little property variation and little volume expansion on wall (thus $v/u \rightarrow 0$), the y_a^+ is in the order of 10 to 26 (ref. 12), which gives a product of $u_a^+ y_a^+$ in the range of 100 to 400. Figure 4 shows that as $v/u_b \rightarrow 0$, the trend of the data points to that general range.

Extension to High Pressure Range

So far the study has been limited to the low-pressure range of less than 50 psia (34.5 N/cm^2). It is interesting to see whether the analytical program can be applied to the entire subcritical pressure range (P_{cr} = 187.7 psia (129.4 N/cm^2)).

Results

Some runs of reference 1 in the pressure levels of 100, 140, and 170 psia (68.9, 96.5, 117 N/cm^2) are tested on the analytical program. The predicted values of heat transfer coefficient h_{anal} are shown in curves as the function of the quality x in figure 5. The experimental value h_{exp} with approximately corresponding conditions are shown as data points. The circles show the dependence of h_{exp} on the equilibrium quality x_{eq}, and the squares show the result based on the nonequilibrium assumption, which will be discussed in the next section. It is evident that the discrepancy between h_{anal} and h_{exp} widens as pressure increases. Therefore, although the analytical approach has been fairly successful in predicting heat-transfer coefficient up to p = 100 psia (68.9 N/cm^2), the underpredicting becomes increasingly serious as pressure is raised.

Discrepancy Under High Pressure

The failure of the analytical model to reasonably predict heat-transfer coefficients in the high-pressure region can be traced to several sources. Reference 1 discusses in detail the difficulties encountered in setting up a model for boiling two-phase flow. The major sources of difficulties are:

(1) Nonequilibrium state - the subcooled liquid coexists with saturated or highly superheated vapor; thus, the true quality of the two-phase flow is quite different from the quality calculated on the assumption of thermodynamic equilibrium. Such nonequilibrium is more serious as the critical state is approached because of the increased time required to achieve the thermodynamic equilibrium state (or saturation condition). In the critical region, the nonequilibrium state can last several days (ref. 17). Such a time scale is very long compared with the residence time of a particle travelling with a speed of 100 feet per second (32.8 m/sec) in a tube 1 foot long (0.328 m long).

(2) Acceleration of flow - All the conventional models for turbulent flow are proposed for a flow in the steady, fully developed state. No provision has been made to correct for the effect of strong accelerations due to large expansion of volume (except perhaps

those accelerations implicitly accounted for by the ratio q/u_b in β). Such an effect is still to be studied.

(3) Uncertainty of bulk slip ratio - Because of the difference in concentration-distribution profiles for the liquid and slip between the liquid and vapor phases, the bulk mean velocities of liquid and vapor are different; therefore, the bulk slip ratio is, in general, different from unity. On the other hand, because the lack of information about this slip ratio, usually a homogeneous distribution of liquid and vapor (with slip ratio equal to one) is assumed in the literature to compute void fraction from quality.

There are uncertainties in the analytical approach in proper comprehending each of these effects. In particular, the effect of acceleration was not considered except perhaps through the parameter β. For the nonequilibrium effect, superheated vapor film has been assumed to coexist with saturated two-phase flow in the bulk, and, also, the droplet distribution is assumed to be different from the homogeneous model. The combined effect of these two assumptions would produce a quality x_{anal} for a given void differing from that based on equilibrium-homogeneous model x_{eq} for the same α_v. Such a result is shown in table III and figure 6. Note that $x_{anal} - x_{eq}$ varies with both pressure and wall temperature. Such a trend is interesting because the large departure from equilibrium quality at higher pressure and higher wall temperature may account for the discrepancy in figures 5(a) to (c), since the h_{exp} were plotted against x_{eq}. It would be interesting to use table III to find the corresponding x_{anal} for each x_{eq}, then plot h_{exp} against x_{anal}. Such a result is shown as the data points in figure 5. The correction of data using analytical quality did not improve the agreement with the analytical curve, apparently because the bulk void was still computed from the equilibrium quality using a homogeneous model. A more thorough approach would be to iterate the bulk enthalpy of the flow to match that obtained from inlet enthalpy plus heat addition. Unfortunately, the present computer program is not readily adaptable to such a scheme.

Although the analytical program apparently failed to predict even qualitatively the experimental result at high pressures, the comparison does show that the main problems for mist-flow film boiling are in the high-pressure region. It also shows an increasing deviation of void relation from that based on the equilibrium-homogeneous model. Thus, for the high-pressure region, the analytical program still serves the useful purpose of being a tool of analysis and diagnosis in uncovering the problem areas.

SIMPLIFIED COMPUTATION FOR DESIGN PURPOSE

The results in this paper demonstrate that a single-phase variable-property approach can be applied to a problem of heat transfer to mist flow. However, for a design engineer, it would be desirable if a simple approximation to the analytical model could be devised. One approach would be to represent the variable properties by a set of film properties evaluated somewhere between the wall properties and bulk properties. With such film properties, the design engineer could then proceed to use conventional heat-transfer equations for constant properties to evaluate the heat-transfer coefficient. A similar approach has been used by Deissler and Presler to give a reference temperature for several gases (ref. 13).

In the mist-flow heat-transfer case, the properties are functions of both temperature and void. Thus, a film temperature T_f and a film void $\alpha_{v,f}$ should be computed. Let T_f and $\alpha_{v,f}$ be expressed as

$$T_f = T_b + C(T_o - T_b) \tag{33}$$

$$\alpha_{v,f} = \alpha_{v,b} + C(1 - \alpha_{v,b}) \tag{34}$$

$$\alpha_{l,f} = 1 - \alpha_{v,f} \tag{35}$$

If the physical properties (evaluated from eq. (1) using these $T_f(C)$ and $\alpha_f(C)$) are substituted into a constant-property heat-transfer equation, an h_{cal} will result for each given value of C. In the case of forced convection, the Dittus-Boelter equation is most widely used. Therefore, a set of $h_{cal}(C)$ is calculated for a given flow condition by use of the Dittus-Boelter equation

$$Nu_f = 0.023(Re_f)^{0.8}Pr_f^{0.4} \tag{36}$$

Figure 7 shows a typical example in the form of a plot of h_{exp}/h_{cal} against C. It is apparent that only one particular C will make the ratio h_{exp}/h_{cal} one, and this value of C, denoted as C_{exp}, is the one that should be used to evaluate the film properties for the prediction of h_{exp} for the given flow condition. If the heat-transfer coefficient can be predicted analytically, a corresponding C_{anal} can also be determined by proper choice of C such that $h_{anal}/h_{cal}(C)$ is one. In this report, the values of h_{exp} were obtained from reference 1, the corresponding value of h_{anal} were obtained from the analytical computing program developed in the previous section, and the $h_{cal}(C)$ were obtained from Dittus-Boelter equation.

Since C_{anal} and C_{exp} vary with the flow conditions, it is instructive to compare the qualitative trends of C_{exp} and C_{anal} as functions of void fraction, wall temperature, tube diameter, and pressure. Such comparisons will be made in the following sections.

Effect of Mean Void Fraction

The effect of mean void fraction (see eq. (4a)) on C_{anal}, holding other conditions constant (pressure 45 psia (31 N/cm^2) T_o at 250° and 680° R (139° and 378° K), respectively), are shown in figure 8. The corresponding data for C_{exp} are also shown for comparison. The two sets of data do not exactly coincide. However, the general trend is the same, namely, both C_{exp} and C_{anal} staying relatively constant at low $\overline{\alpha}_v$ and decreasing rapidly as $\overline{\alpha}_v$ approaches unity. It should be noted that C could be extrapolated to the neighborhood of 0.5 for the all-gas case of $\overline{\alpha}_v = 1$. Such a trend is interesting because the conventional correlation of the forced-convective heating of gas stipulates the reference temperature to be $T_f = T_b + 0.4(T_o - T_b)$ (ref. 13).

It should also be noted that even though the C_{anal} and C_{exp} curves do not coincide, their difference is most significant when C is small. From figure 7, it can be seen, that for small C, the h_{cal}/h_{exp} does not vary greatly. In other words, a variation of C when C is small would not greatly affect the ratio of h_{exp}/h_c. However, the variation of C is more critical as C approaches unity. Fortunately, the C_{anal} and C_{exp} are quite close when the value of C is close to one, thereby improving the agreement between theory and experiment.

Since $\overline{\alpha}_v$ was found to be the primary parameter controlling C, most of the subsequent figures showing the effects of other parameters will be plotted in the form of C against $\overline{\alpha}_v$.

Effect of Wall Temperature

Figure 8 shows that the theoretical curves for $T_o = 250°$ R (139° K) are nearly parallel to those for $T_o = 680°$ R (378° K) but somewhat higher in the value of C. Again, by the same argument in the previous section, the parallel shift indicates that the wall-temperature effect increases with increasing $\overline{\alpha}_v$.

The experimental effect of T_o on C is shown in figure 9 in the form of C_{exp} against T_o for various ranges of $\overline{\alpha}_v$. It appears that the C_{exp} against T_o curves go through a shallow maximum in the vicinity of $T_o = 400°$ to 500° R (220° to 280° K). But in general, the curves are fairly flat, indicating a lesser dependence than predicted theoretically.

Effect of Tube Radius

The effect of tube radius on C_{anal} is shown in figure 10. From this figure, it appears that a change in the tube radius as great as a factor of 3 does not significantly change C provided the pressure and T_o are low. Increasing either temperature or pressure tends to increase the downward shift of the C curve for a larger diameter.

A similar trend is observed for C_{exp}. In figure 11, three lines, one for each of three tube radii, of the ratio of C_{exp} to C_{emp} calculated from equation (37) (discussed the section EMPIRICAL CORRELATION) are plotted against pressure over a wide range of T_o. It appears again that C_{exp}/C_{emp} curves for different radii coincide at the low-pressure range while curves for the larger tubes drop more rapidly at higher pressure. Note that the ratio C_{exp}/C_{emp} should be approaching unity with decreasing pressure because C_{emp} is an empirical fit based on low-pressure data.

Effect of Pressure

Up to last section, most of the discussion of results concerning the coefficient C was limited to the low-pressure (50 psia, 34.5 N/cm^2) region, except for a few remarks on the effect of tube diameter on C under higher system pressure. It appears that in the low-pressure region, the C_{anal} and C_{exp} follow the same trend in their response to the variation of parameters such as void fraction wall temperature and tube diameter. It would be interesting to examine the behavior of C_{anal} and C_{exp} in the entire sub-critical pressure range.

In the higher end of subcritical pressure range ($1 > P/P_{cr} > 0.25$, $P_{cr} > P > 50$ psia, 34.5 N/cm^2), effects of pressure on C are more complicated. As shown in figure 11, the best fit curves of C_{exp} against pressure dip gradually with increasing pressure. However, the C_{anal} curves in figure 12 show an entirely different trend. The C_{anal} curves actually shift upward with increasing of pressure. Therefore, for a given pressure, C_{anal} obtained in figure 12 is higher than the corresponding C_{exp} given in figure 11. Since an increase in C means a decrease in h; the higher value of C_{anal} means that h_{anal} is underpredicting the value of h_{exp}.

EMPIRICAL CORRELATION

As it was discussed in the previous section, the C_{anal} tends to underpredict the heat-transfer coefficient. On the other hand, C_{exp} was fairly flat with respect to pressure. Thus, before some means can be found to take into account the nonequilibrium state and the acceleration effect, an empirical correlation will have to be used. In view of the fact that C_{exp} is primarily dependent upon $\overline{\alpha}_v$, while only mildly affected by T_o, r, and P, a best-fit curve is determined from $C_{exp}(\overline{\alpha})$ as

$$C_{emp} = \frac{0.964\ \bar{\alpha}_v - 0.9684}{\bar{\alpha}_v - 1.02} \tag{37}$$

The heat-transfer coefficients calculated by using C_{emp} given by equation (37) are then compared with the experimental h. The result is shown in figure 13. The figure shows that 73 percent of the data points are within ±20 percent error, and 88 percent are within ±35 percent error. If the range in pressure is limited to less than 100 psia (68.9 N/cm^2), then almost all the data points are within the ±35 percent band; 90 percent are within a ±25 percent band.

Such a correlation scheme predicts the heat-transfer coefficient for film-boiling hydrogen (25 to 170 psia (17.2 to 117 N/cm^2); T_o, 250° to 700° R (139° to 389° K); $\bar{\alpha}_v$, 0.5 to 1.0; D, 1/4 to 1/2 in. (0.635 to 1.27 cm)) with accuracy comparable to those schemes proposed before, such as χ_{tt}-method, etc. (ref. 1). But the present scheme has the advantage of being simple. Besides, the similarity in trends between C_{anal} and C_{exp} renders support to its credibility.

This empirical correlation scheme can be summarized as follows:

(1) Compute mean void fraction from equation (4a).

(2) Compute the film coefficient C_{emp} from equation (37).

(3) Compute the reference temperature T_f from equation (33), the reference void $\alpha_{v,f}$ from equation (34), and the reference liquid volume fraction $\alpha_{l,f}$ from equation (35).

(4) Compute synthesized properties according to equation (1).

(5) Compute Nusselt number using equation (36).

CONCLUSIONS

In this report, an analytical program is developed and is tested against experimental data in both the low-pressure (<50 psia, 34.5 N/cm^2) and the high-pressure (>50 psia) regions. An empirical correlation scheme was proposed for design purposes. The comparison between the analytical results, the experimental data, and the empirical scheme lead to the following conclusions:

1. It appears that the film-boiling mist flow can be treated as a variable-property single-phase flow using Deissler's approach with modification. The heat-transfer coefficient predicted by such a model is within 35 percent error for the low-pressure hydrogen (<50 psia or 345 N/cm^2).

2. The discrepancy between h_{anal} and h_{exp} at high pressure was attributed to the existence of a nonequilibrium state and the acceleration effect on turbulence. Detailed analysis showed that quality computed from the analytical model was quite different

from that computed from homogeneous-equilibrium concepts for the same void fraction. The analytical program, although relatively inconvenient to use because of the long computer time required, is a powerful tool for diagnosis of the mist-flow problem. The discussion on pressure effect was an example.

3. For the evaluation of h, it was found that the Dittus-Boelter equation could be used, provided properties were evaluated at a reference temperature and reference void which were determined by a coefficient C. The C's determined from the analytical model C_{anal}, and that from experimental data, C_{exp} showed the same trends for the effect of void, wall temperature, and tube diameter, in the low-pressure region. But C_{anal} failed to give the same trend as that of C_{exp} in predicting the effect of pressure, especially when the pressure approached the critical point.

4. An empirical correlation of C as function of $\bar{\alpha}_v$ has been devised. The use of $\bar{\alpha}_v$ as the sole independent variable is supported by the trend of C_{anal}, which shows only weak dependence on wall temperature and tube diameter. The pressure effect is left unanswered because the analytical program showed that more investigation is needed in this respect.

5. The recommended empirical correlation scheme has the merit of being simple and easy to use. The correlation predicts 73 percent of data points within 20 percent error band and 88 percent within 35 percent error band.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, March 30, 1967,
129-01-11-02-22.

APPENDIX A

SYMBOLS

C film coefficient to determine reference temperature and void (eqs. (33) and (34))

C_p specific heat under constant pressure, Btu/(lb)(^oF); J/(kg)(^oK)

d diameter, ft (cm)

f friction factor, $\tau/(\rho u_b^2/2)$

H enthalpy, Btu/lb; J/kg

h heat transfer coefficient, Btu/(ft^2)(hr)(^oR); J/(cm^2)(hr)(^oK)

K thermal conductivity, Btu/(hr)(ft)(^oR); J/(cm^2)(hr)(^oK)

L length from inlet, in.; cm

m exponent in eq. (5b)

Nu Nusselt number

n constant, 0.124

P pressure, psia; N/cm^2

Pe Péclet number

Pr Prandtl number

q heat flux, Btu/(ft^2)(hr); J/(cm^2)(hr)

Re Reynold number

r radius, ft; cm

r^+ dimensionless radius

St Stanton number

T temperature, ^oR; ^oK

T^+ dimensionless temperature

u velocity, ft/sec; m/sec

u^+ dimensionless velocity

u^* friction velocity, $\sqrt{\tau_o/\rho_o}$, ft/sec; m/sec

v transverse velocity, ft/sec; m/sec

$\dot{w}$ mass flow rate, lb/sec; (kg/sec)

X quality, lb/lb; kg/kg

y distance from wall, ft; m

y^+ dimensionless distance

α volume fraction

β heat-transfer parameter

Δ difference

ϵ eddy diffusivity, ft^2/sec; m^2/sec

ϵ^+ dimensionless eddy diffusivity

κ 0.36, constant

λ latent heat, Btu/lb; J/kg

μ viscosity, lb/(ft)(sec); kg/(m)(sec)

ν kinematic viscosity, ft^2/sec; m^2/sec

ρ density, lb/ft^3; kg/m^3

τ shear stress, lb force/ft^2; N/m^2

φ properties in general

Subscripts:

A analogy

a transition between wall region and core region

anal analytical

b bulk

c	convection
cal	calculated
CL	centerline
cr	critical
D	definition
emp	empirical
eq	equilibrium
exp	experimental
f	film
h	enthalpy flux
l	liquid
m	momentum
o	wall
pg	perfect gas
sat	saturation
t	thermal
v	gas, or vapor
w	wanted

Superscript:

—	mean

APPENDIX B

COMPUTER PROGRAM

Presented in this appendix are a listing of subprograms, a description of subprograms, an input/output format, and a flow diagram. Program listings are accompanied by a table of nomenclature with FORTRAN and mathematical notations.

LISTINGS OF SUBPROGRAMS

The program consists of a main program plus the following subroutines:

Subroutine Name	Deck Name
START	STARTT
FINISH	FINNISH
CALC	CALCC
PROPTY(Y, TEMP)	PRPETY
SPHT	CURFIT
VISC	CURFIT
THCON	CURFIT
HOVAP	CURFIT
SATDEN	CURFIT
SATRT	CURFIT
STATES	STATES
STATE	STATE

DESCRIPTION OF SUBPROGRAMS

MAIN PROGRAM Sets some constants for STATE and STATES and calls sub START

START Reads input data. If certain data are not input, it makes a guess at initial values for these variables. Computes wall properties.

CALC	Main computation routine. Solves the differential equations as specified in the text. The Runge-Kutta method is used to solve the differential equations. Simpson's rule is used for the indicated integrations (See ref. 18 for methods of integration). It consists of four parts: (1) near the wall unsaturated, (2) near the wall saturated, (3) away from wall unsaturated, (4) away from the wall saturated.
FINISH	Tests for convergence of $\dot{w}$, $\overline{\alpha}_{CL}$, and BETA when $y^+ = r^+$ in CALC. When all these conditions are satisfied, it computes and prints out final results; then solves for C such that $h \approx h_2$ at the end and calls subroutine START for a new case.
PROPTY	Gets the proper hydrogen properties depending on whether conditions are saturated or unsaturated, then computes some ratios.
CURFIT	MAP subroutine which has curve fit approximation of liquid and vapor hydrogen properties.
STATE	Computes real fluid-state relation, thermodynamic properties, and transport properties of molecular H_2 (see ref. 19).
STATES	Initializes values for STATE.
TIME I(X)	Library subroutine available at Lewis that interrogates the storage cell clock and returns to calling program with a floating point number in x, which is in clock pulses with period of 1/3600 minute. If a time clock routine is not available, a fake subroutine with name TIME I(X) must be inserted into the program deck.

DESCRIPTION OF INPUT/OUTPUT

Description of Input Data

Four data cards are necessary for each case, they are

(1) Title - The first card of each case contains a descriptive heading which will appear in the output to aid in identification of the case.

(2) The second card specifies

TO	wall temperature, $^{\circ}R$
TB	bulk temperature, $^{\circ}R$
PSTAT	static pressure, $lb_f/in.^2$
UBULK	bulk velocity, ft/sec
R	radius of pipe, in.
X	quality
WWANT	desired $\dot{w}$, lbm/sec

(3) The third card specifies

ELL	length this station is from the tube inlet (identification only), in.
BNDRY	value of where transition to away-from-wall is made
DELY	Δy step on y for integration procedure
DELU	Δu step on u for integration procedure
RITE1	switch if not equal to 0, no print; if equal to 0 print at each integration step in near wall unsaturated
RITE 2	switch if not equal to 0, no print; if equal to 0 print at integration step in near wall saturated
RITE 3	switch if not equal to 0, no print; if equal to 0, print at each integration step away from wall unsaturated
RITE 4	switch if not equal to 0, no print; if equal to 0, print at each integration step in away from wall saturated

(4) The fourth card specifies

BETA

RPLUS

UPLCL

ALFCL

ZMAXTM maximum amount of computer time to be used for this case. If ZMAXTM ≤ 0, it will be set to 60 minutes by the program. See description of time clock routine TIME I(X) in previous section.

If the quantities, BETA, RPLUS, UPLCL, ALFCL, are unknown at the beginning of a case, leave the first four fields of this card blank. Note however, that first guesses of all four variables will be computed if only the first field is left blank or is equal to 0. If the first field is not blank or is equal to 0, the values used for the first guess for all four variables are read from the card.

Input Format

Card (1) TITLE

1 All 80 columns may be used for the title 80

Card (2)

1 — 10	11 — 20	21 — 30	31 — 40	41 — 50	51 — 60	61 — 70
TO	TB	PSTAT	UBULK	R	X	WWANT
X.XX	X.XX	X.XX	X.XX	X.XX	X.XX	X.XX

Card (3)

1 — 10	11 — 20	21 — 30	31 — 40	41 — 50	51 — 60	61 — 70	71 — 80
ELL	BNDRY	DELY	DELU	RITE1	RITE2	RITE3	RITE4
X.XX	X.XX	X.XX	X.XX	X.XX	X.XX	X.XX	X.XX

Card (4)

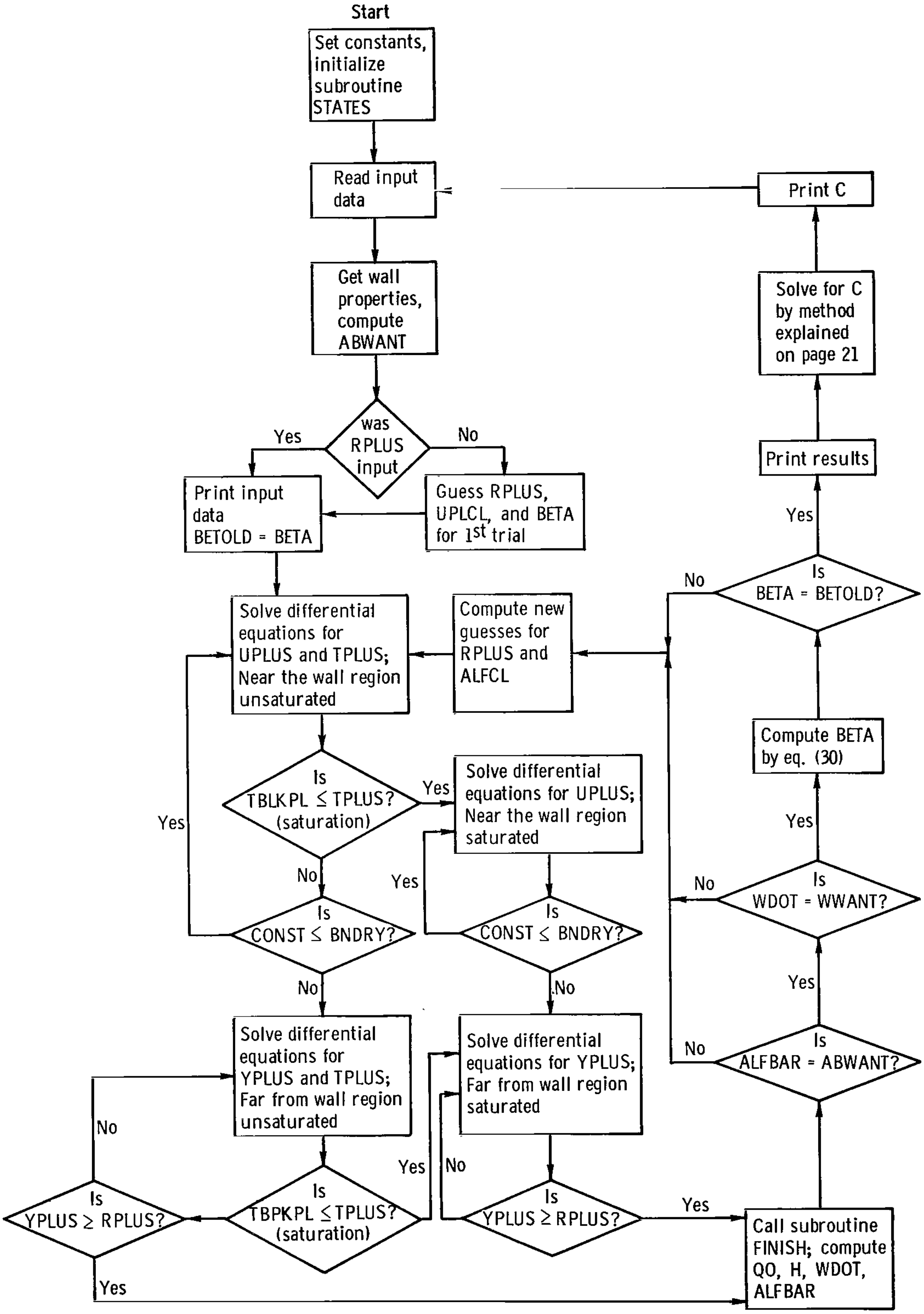
1 — 10	11 — 20	21 — 30	31 — 40	41 — 50
BETA	RPLUS	UPLCL	ALFCL	ZMAXTM
X.XX	X.XX	X.XX	X.XX	X.XX

Input Data Cards for Sample Case

```
CASE NO. 18-2, L=8.44          SAMPLE CASE
 252.7    43.7     40.7     170.6    .1565    .062     .177
 8.44      2.0      .125     .0025   1.0      1.0      1.0      1.0
 .05782   1464.13  13.4195  .55484   60.
```

Computer Output of Sample Case

```
CASE FINISHED, FINAL OUTPUT.

                    CASE NO. 18-2, L=8.44        SAMPLE CASE

 INPUT THIS CASE

   TO       TB       PS       UBULK       L        BNDRY    R          X          WWANT      ABWANT     DELY       DELU
 252.700   43.700   40.700   170.600     8.440     2.000   0.15650    0.06200    0.17700    0.55929    0.12500    0.00250

WALL AND FILM PROPERTIES
 CP,O         MU,O         K,O          RHO,O        RHOL         PR,O         CP,F         MU,F         K,F          PR,F
 3.83414      3.64154E-06  1.77143E-05  3.02095E-02  4.05869      0.78818      2.79925      2.40676E-06  9.66851E-06  0.69681
 FINAL RESULTS THIS CASE
   R+          U+CL         ALFCL
 1423.830     13.50274     0.548794
   U+          Y+           T+           UBLK+        XT(PART)     ALPHA        RHOBAR       RHO*U+       RE
 13.5028      1551.28      14.4447      12.9632      0.59524E-01  0.54879      1.94725      26.2932      40219.1

 BETA         NU,O         TAU,O        RE,O         Q,O          WDOT         ALFBAR       XT           H            TIME USED(MIN)
 5.7099E-02   1.8770E 02   5.3033E 00   3.6915E 04   1.8501E-01   1.7641E-01   5.6116E-01   5.9524E-02   8.8523E-04   1.0853E 00

 TRANSITION POINT FROM NEAR WALL TO FAR FROM WALL REACHED AT NEAR WALL UNSATUATED
   CONST= 1.48284     MU= 0.68356     YPLUS= 8.50000     UPLUS= 7.61338

  TOTAL NO. OF TIMES THRU CALC FOR THIS CASE=   19, TOTAL MACHINE TIME USED THIS CASE =    20.64 MIN.
END OF CASE C=      0.9762635      H=       0.0008852       H2=       0.0008895

*01* UNIT05, EOF.                                                                         REC=  00000 FIL=
```



Flow diagram of program

Computer Nomenclature

FORTRAN symbol	Engineering symbol	Definition
ABWANT	$\bar{\alpha}_{v,w}$	desired value of $\bar{\alpha}$
ALFBAR	$\bar{\alpha}_v$	value computed by program
ALFCL	$\alpha_{v,cL}$	void fraction at centerline
ALPHA	α_v	local void fraction
BETA	β_A	refers to the expression of heat-transfer parameter as derived from momentum and heat-transfer analogy computed by equation (30).
BETOLD	--	temperature parameter used as BETA for computations and compared with BETA of equation (30) at end of each iteration
BNDRY	ϵ_a^+	value of $(\epsilon/\nu) = \epsilon^+$ to be compared with, to test for transition point from near wall to away from wall (see eqs. (12) and (13))
C	C	film coefficient to determine set temperature and void
CAPPA	κ	constant 0.36
CONST	ϵ^+	computed in program
CONV	--	input data for subroutine STATES (see ref. 18)
DELU	--	step size for integration with respect to u
DELY	--	step size for integration with respect to y
ELL	l	distance down tube (identification only)
H	h_{exp}	heat-transfer coefficient
H^2	h_{cal}	heat-transfer coefficient computed by film coefficient C
PRANO	Pr_o	Prandtl number at wall
PSTAT	P	static pressure
QO	q_o	heat flux at wall
R	r	radius
RE	Re	Reynolds number

RPLUS	r^+	dimensionless radius
TB	T_b	bulk temperature
TBLKPL	T_b^+	dimensionless bulk temperature
TEST	---	threshold for iteration on $\dot{w}$ and α_{cL}
TESTB	---	threshold for iteration on β
TO	T_o	wall temperature
TPLUS	T^+	dimensionless temperature
UBLKPL	u_b^+	dimensionless bulk velocity
UBULK	u_b	bulk velocity
UNITS	---	input for subroutine STATES (see ref. 18)
UPLCL	u_{CL}^+	dimensionless centerline velocity
UPLUS	u^+	dimensionless velocity
VG	---	input for subroutine STATES usually ≈ 0.25 (see ref. 18)
VL	---	input for subroutine STATES usually ≈ 4.0 (see ref. 18)
WDOT	$\dot{w}$	mass flow rate computed by program
WWANT	$\dot{w}_w$	desired value of mass flow rate
X	x	input quality
XT	---	final integrated quality computed by program
XTPRT	---	local quality during computation (partial sum)
YPLUS	y^+	dimensionless distance

PROGRAM LISTINGS

```
C FILM-BOILING MIST-FLOW MAIN PROGRAM
C
C MAIN PROGRAM INITIALIZES SOME CONSTANTS, THEN, ONLY CALLS
C SUBROUTINES TO DO THE COMPUTING.
      COMMON/STATE1/STORE(50)/STATE2/UNITS,COMP,CONV
      EQUIVALENCE (VL, STORE(15)), (VG, STORE(16))
      VG=0.25
      VL=4.0
      CONV=1.0E-06
      UNITS=-1.0
      CALL STATES
   10 CALL START
      WRITE (6,100)
      GO TO 10
  100 FORMAT(55HLRETURNED TO MAIN PROGRAM BY SOME ERROR GO TO NEXT CASE)
      END
```

```
$IBFTC STARTT

      SUBROUTINE START
C
C  REAL COMMON NAMES
C
      COMMON    ABWANT, AK    , AKE   , AKO   , ALFBAR, ALFCL , ALPHA ,
     1 ALRHO , AMU   , AMUF  , AMUL  , AMUO  , AMUV  , BETA  , BNDRY ,
     2 CAPPA , CP    , CPFCPO, CPGF  , CPO   , DALDY , DELT  , DELTA ,
     3 DUSAVE, DYSAVE, FLL   , EN    , ENDTM , ENSQ  , EPSTR , FODEN ,
     4 HG    , PRANO , PRF   , PSTAT , PTEMP , R     , RE    , REO   ,
     5 RHO   , RHO1  , RHOL  , RHOO  , RHOU  , RHOV  , RITE1 , RITE2 ,
     6 RITE3 , RITE4 , RPLUS , SNSLT4, STRTTM, TB    , TBLKPL, TITLE ,
     7 TO    , TOTIME, TPLUS , TSAT  , TT    , UBLKPL, UBULK , UPLCL ,
     8 UPLUS , WWANT , X     , XT    , XTDEN , XTNUM , XTPRT , YPLUS ,
     9 ZMAXTM
C
C  INTEGER COMMON NAMES
C
      COMMON    ITERNO, NBEGIN, NOBITR, NTIMES
C
C  LABELED COMMON
C
      COMMON/STATE1/STORE(50)/STATE2/UNITS,COMP,CONV
C
C  DIMENSIONED COMMON
C
      DIMENSION    TITLE(14)
      EQUIVALENCE (COM,ABWANT)
      DIMENSION COM(92)
      DATA PI/3.14159265/
      DO 1200 I=1,92
 1200 COM(I)=0.
   10 CAPPA=0.36
      EN=0.124
      ENSQ=EN*EN
      READ(5,100) TITLE,TO,TB,PSTAT,UBULK,R,X,WWANT,ONITER,FLL,BNDRY
     1 ,DYSAVE,DUSAVE,RITE1,RITE2,RITE3,RITE4
C
      READ(5,350) BETA,RPLUS,UPLCL,ALFCL,ZMAXTM
C  IF IT IS DESIRED TO HAVE PROGRAM GUESS INITIAL VALUES FOR BETA, RPLUS
C  UPLCL, AND ALFCL LEAVE FIRST 4 FIELDS OF THIS CARD BLANK.
C
      IF(ZMAXTM .LE. 0.) ZMAXTM=60.0
C GET WALL PROPERTIES AND CONSTANT TERMS TO FIND BETA
 1000 CALL SPHT (TO    ,99,CPO)
      CALL VISC (TO    ,99,AMUO)
      CALL THCON(TO    ,99,AKO)
      CALL HOVAP(PSTAT,ALAMDA,99)
      STORE(6)=PSTAT
      STORE(7)=TO
      CALL STATE(3)
```

```
      V=STORE(8)
      RHOO=1.0/V
      HTO=STORE(12)
      STORE(7)=TB
      CALL STATE(3)
      V=STORE(8)
      RHOV=1.0/V
      HSAT=STORE(12)
      HG=ALAMDA+HTO-HSAT
 1106 CALL SATDEN(PSTAT,RHOL,99)
      RRHOB= X/RHOV + (1.0-X)/RHOL
      IF(TB) 400,401,400
  401 CALL SATRT(PSTAT,TB,99)
  400 IF(UBULK) 402,403,402
  403 UBULK=144.0*WWANT*RRHOB/(PI*R*R)
  402 ABWANT=(X/RHOV)/RRHOB
      PRANO=CPO*AMUO/AKO
      REO=R/6.0*UBULK/AMUO*RHOO
      TF=(TO+TB)/2.
      CALL SPHT(TF,99,CPGF)
      CALL VISC(TF,99,AMUF)
      CALL THCON(TF,99,AKF)
      PRF=CPGF*AMUF/AKF
      FODEN=RHOO*UBULK*UBULK
      CPFCPO=CPGF/CPO
      WRITE(6,102) TITLE,TO,TB,PSTAT,UBULK,ELL,BNDRY,R,X,WWANT,ABWANT
     1 ,DYSAVE,DUSAVE,CPO,AMUO,AKO,RHOO,RHOL,PRANO,CPGF,AMUF,AKF,PRF
     2 ,ZMAXTM
  301 DELT=TO-TB
      IF(ONITER.EQ. 0.) ONITER=1.
      ITERNO=ONITER
      IF(RPLUS.NE. 0.) GO TO 105
C
C  GUESS RPLUS, ALFACL, U+CL, AND BETA FOR FIRST TRIAL IF NOT INPUT ABOV
C
      UPLCL=10.
      RPLUS=UBULK*R*RHOO/(120.*AMUO)
      ALFCL=ABWANT
      TAUO=120.*UBULK*AMUO/R
      SRFOO2= SQRT(TAUO/FODEN)
      BETA=DELT/TO*SRFOO2*(1./PRF+1.)/2.*CPFCPO
  105 WRITE (6,101)ITERNO,BETA,RPLUS,UPLCL,ALFCL
      CALL CALC
      RETURN
  100 FORMAT(13A6,A2/(8F10.2))
  101 FORMAT(40HL THIS CASE STARTING WITH ITERATION NO.  I4,34H  AND STA
     1RTING VALUES AS FOLLOWS  /1HJ,4X,4HBETA,11X,5HRPLUS,10X,5HUPLCL,
     2 10X,6HALFCL  / 5G15.5)
  102 FORMAT(1H1,23X,13A6,A2/17HK INPUT THIS CASE/1HK,4X,2HTO,8X,2HTB,8X
     1 ,2HPS,7X,5HUBULK,6X,1HL,9X,5HBNDRY,4X,1HR,9X,1HX,9X,5HWWANT,4X,
     2 6HABWANT,5X,4HDELY,6X,4HDELU/6F10.3,6F10.5/
     3 25HKWALL AND FILM PROPERTIES/2X,4HCP,O,9X,4HMU,O,9X,3HK,O,10X
     4 5HRHO,O,8X,4HRHOL,9X,4HPR,O,9X,4HCP,F,9X,5H MU,F,8X,4H K,F,9X,
     6 4HPR,F/1P10G13.5/59HKMAXIMUM AMOUNT OF COMPUTER TIME TO BE USED F
     7OR THIS CASE = 0PF7.2,9H MINUTES.)
  350 FORMAT(8F10.2)
```

```
$IBFTC FINNSH
      SUBROUTINE FINISH
      DATA CMIN,CMAX,H2MIN,H2MAX/0.,0.,0.,0./
      DATA TEST1,TEST2,NTEST/ 0.10,0.005, 1/
      DATA TESTB1/0.05/
      DATA TEST,TESTB/0.1,0.05 /
C
C  REAL COMMON NAMES
C
      COMMON   ABWANT, AK    , AKF   , AKO   , ALFBAR, ALFCL , ALPHA ,
     1 ALRHO , AMU   , AMUF  , AMUL  , AMUO  , AMUV  , BETA  , BNDRY ,
     2 CAPPA , CP    , CPFCPO, CPGF  , CPO   , DALDY , DELT  , DELTA ,
     3 DUSAVE, DYSAVE, ELL   , EN    , ENDTM , ENSQ  , EPSTR , FODEN ,
     4 HG    , PRANO , PRF   , PSTAT , PTEMP , R     , RE    , REO   ,
     5 RHO   , RHO1  , RHOL  , RHOO  , RHOU  , RHOV  , RITE1 , RITE2 ,
     6 RITE3 , RITE4 , RPLUS , SNSLT4, STRTTM, TB    , TBLKPL, TITLE ,
     7 TO    , TOTIME, TPLUS , TSAT  , TT    , UBLKPL, UBULK , UPLCL ,
     8 UPLUS , WWANT , X     , XT    , XTDEN , XTNUM , XTPRT , YPLUS ,
     9 ZMAXTM
C
C  INTEGER COMMON NAMES
C
      COMMON   ITERNO, NBEGIN, NOBITR, NTIMES
C
C  LABELED COMMON
C
      COMMON/STATE1/STORF(50)/STATE2/UNITS,COMP,CONV
      COMMON/TRANSI/TRPT,TRC,TRA,TRY,TRU
C
C  DIMENSIONED COMMON
C
      DIMENSION   TITLE(14)
      STOP=0.0
      NTIMES=NTIMES+1
      XT=XTNUM/XTDEN
      ANU=2.0*RPLUS*PRANO/TBLKPL
      TAUO=  UBULK*AMUO*12.0*RPLUS /(R*UBLKPL)
      USTAR=SQRT(TAUO/RHOO)
      EPS=EPSTR*AMUO/RHOO
      YSTAR=AMUO/(RHOO*USTAR)
      DALDY=DALDY/YSTAR
      QHO=EPS  *HG*RHOO*DALDY /144.0
      QCO=ANU*AKO*DELT/(24.0*R)
      QO=QCO+QHO
      WDOT=6.2831976 *XTDEN*((AMUO/RHOO)**2)/USTAR
      ALFBAR=2.*ALFBAR/(RPLUS*RPLUS)
      H=QO/DELT
      ANUO=24.*H*R/AKO
      CALL TIME1(ENDTM)
      DIFTM=(ENDTM-STRTTM)/3600.
      TOTIME=TOTIME+DIFTM
```

```
       FINNSH      -  EFN    SOURCE STATEMENT  -  IFN(S)  -

      WRITE(6,200) BETA,ANUO,TAUO,REO,QO,WDOT,ALFBAR,XT,H,DIFTM,TEST,
     1 TESTB
      WFRACT=(WWANT-WDOT)/WWANT
      IF((ABS(ALFBAR-ABWANT)/ABWANT).GT. TEST) GO TO 20
      IF(ABS(WFRACT) .GT. TEST) GO TO 20
      BETOLD=BETA
      SRFOO2= SQRT(TAUO/FODEN)
      BETA=DELT/TO*SRFOO2*(1./PRF+1.)/2.*CPFCPO
      RPLUS=R*UBULK*RHOO/(12.0*AMUO*UBLKPL)
      IF(ABS(BETA-BETOLD)/BETA.LT. TESTB) GO TO 23
      ITERNO=0
      GO TO 24
   20 ALFCL=ALFCL+0.2*(ABWANT-ALFBAR)
      IF(ABS(WFRACT) .GE. 1.) WFRACT=ABS(WFRACT)*0.5/WFRACT
      IF(ITERNO.GT.10) WFRACT=WFRACT/2.
      RPLUS=RPLUS+RPLUS* WFRACT
      IF(ITERNO.GT.1) GO TO 21
   24 ALFCL=ABWANT
   21 UPLCL=UPLUS
   22 ITERNO=ITERNO+1
      WRITE (6,204)ITERNO,BETA,RPLUS,UPLCL,ALFCL
      IF(TOTIME .LT. ZMAXTM) GO TO 2000
      WRITE(6,2001) TOTIME,ZMAXTM
      STOP=0.1
      GO TO 232
 2000 CALL CALC
   23 GO TO (230,231),NTEST
  230 NTEST=2
      ITERNO=0
      TEST=TEST2
      TESTB=TEST2
      GO TO 24
  231 WRITE(6,205)
  232 CONTINUE
      WRITE(6,102) TITLE,TO,TB,PSTAT,UBULK,ELL,BNDRY,R,X,WWANT,ABWANT
     1 ,DYSAVE,DUSAVE,CPO,AMUO,AKO,RHOO,RHOL,PRANO,CPGF,AMUF,AKF,PRF
      WRITE(6,206) RPLUS,UPLCL,ALFCL,UPLUS,YPLUS,TPLUS,UBLKPL,XTPRT,
     1 ALPHA,RHOI,RHOU,RE
      WRITE(6,200) BETA,ANUO,TAUO,REO,QO,WDOT,ALFBAR,XT,H,DIFTM
      WRITE(6,2003) TRPT,TRC,TRA,TRY,TRU
      WRITE(6,207) NTIMES,TOTIME
      IF(STOP .NE. 0.0) GO TO 2002
      TSAT=TB
      CALL SPHT(TSAT,CPL,99)
      CALL THCON(TSAT,AKL,99)
      C=(.964*ALFBAR-0.9684)/(ALFBAR-1.02)
      NC=0
      D=2.*R
      CMIN=0.
      CMAX=0.
      H2MIN=0.
      H2MAX=0.
  300 TF=TB+C*(TO-TB)
      NC=NC+1
      ALFF=ALFBAR + C*(1.0-ALFBAR)
      ALFL=1.0-ALFF
```

```
      CALL VISC(TF,99,AMUFV)
      CALL SPHT(TF,99,CPFV)
      CALL THCON(TF,99,AKFV)
      STORE(7)=TF
      CALL STATE(3)
      V=STORE(8)
      RHOFV=1./V
      AKF  = ALFF*AKFV  + ALFL*AKL
      RHOF =ALFF* RHOFV + ALFL*RHOL
      AMUF= ALFF*AMUFV + ALFL*AMUL
      CPF= ALFF*CPFV+ALFL*CPL
      REF= D*UBULK*RHOF/AMUF/12.0
      PRF=CPF*AMUF/AKF
      ANUF=0.023*(REF**0.8)*(PRF**0.4)
      H2=ANUF*AKF/D/12.
      DIFH=H2-H
      IF(ABS(DIFH)/H .LT. 0.005) GO TO 400
      IF(DIFH) 301,400,302
C  H2 .LT. H, DECREASE C
  301 CMAX=C
      H2MAX=H2
      IF(CMIN .GT. 0.) GO TO 350
      C=0.9*C
      GO TO 375
C  H2 .GT. H, INCREASE C
  302 CMIN=C
      H2MIN=H2
      IF(CMAX.GT.CMIN) GO TO 350
      C=1.0
      GO TO 375
  350 FRACT=(H-H2MIN)/(H2MAX-H2MIN)
      C=CMIN+FRACT*(CMAX-CMIN)
  375 IF(NC .LT. 25) GO TO 300
      WRITE (6,1000)
  400 WRITE(6,1001) C,H,H2
 2002 TEST=TEST1
      TESTB=TESTB1
    - NTEST=1
      CALL START
      RETURN
  102 FORMAT(1HL,23X,13A6,A2/17HK INPUT THIS CASE/1HK,4X,2HTO,8X,2HTB,8X
     1 ,2HPS,7X,5HUBULK,6X,1HI,9X,5HBNDRY,4X,1HR,9X,1HX,9X,5HWWANT,4X,
     2 6HABWANT,5X,4HDELY,6X,4HDELU/6F10.3,6F10.5/
     3 25HKWALL AND FILM PROPERTIES/2X,4HCP,0,9X,4HMU,0,9X,3HK,0,10X
     4 5HRHO,0,8X,4HRHOL,9X,4HPR,0,9X,4HCP,F,9X,5H MU,F,8X,4H K,F,9X,
     6 4HPR,F/1P10G13.5)
  200 FORMAT(6HK BETA,8X,4HNU,0,8X,5HTAU,0,7X,4HRE,0,8X,3HQ,0,9X,4HWDOT,
     1 8X,6HALFBAR,6X,2HXT,10X,1HH,11X,14HTIME USED(MIN)/
     2 1P10E12.4,0P2F6.3)
  204 FORMAT(22HL  BEGIN ITERATION NO.  I4, 6H  WITH  /
     1                                           1HJ,3X,4HBETA,12X,5HRPLJ
     2S,11X,4HU+CL,10X,5HALFCL  /1HJ,4G15.6)
  205 FORMAT(30H1 CASE FINISHED, FINAL OUTPUT.)
  206 FORMAT(26H  FINAL RESULTS THIS CASE / 1HJ,4X,2HR+,12X,4HU+CL,12X,
     1 5HALFCL / 3G15.6/1HJ,3X,2HU+,12X,2HY+,10X,2HT+,10X,5HUBLK+,8X,
     3 8HXT(PART),
```

```
    3  6X,5HALPHA,7X,6HRHOBAR,7X,6HRHO*U+,9X,2HRE/ 9G13.5)
  207 FORMAT(47HK  TOTAL NO. OF TIMES THRU CALC FOR THIS CASE= I4,
    1 38H, TOTAL MACHINE TIME USED THIS CASE =  F8.2, 5H MIN.)
 1000 FORMAT(48HK H AND H2 NOT CONVERGED IN 25 ITERATIONS, STOP.)
 1001 FORMAT(15H END OF CASE C= F15.7,5X,2HH= F15.7,5X,3HH2= F15.7)
 2001 FORMAT(37H1 THE TOTAL TIME USED ON THIS CASE, (F6.2,53H MIN.), EXC
     1EEDS THE MAXIMUM ALLOWABLE AS SPECIFIED, (F6.2, 7H MIN.). /
     2  68HK PRINT RESULTS AS THEY EXIST AT THIS TIME, THEN GO ON TO NEX
     3T CASE. )
 2003 FORMAT(72HK TRANSITION POINT FROM NEAR WALL TO FAR FROM WALL REACH
     1ED AT NEAR WALL A6,4HATE)/4X,6HCONST=F9.5,4X,4H MU=F9.5,4X,6HYPLUS
     2=F9.5,4X,6HUPLUS=F9.5)
      END
```

```
$IBFTC CALCC
      SUBROUTINE CALC
C
C   REAL COMMON NAMES
C
      COMMON    ABWANT, AK     , AKF    , AKO    , ALFBAR, ALFCL , ALPHA ,
     1 ALRHO , AMU    , AMUF   , AMUL   , AMUO   , AMUV  , BETA  , BNDRY ,
     2 CAPPA , CP     , CPFCPO, CPGF   , CPO    , DALDY , DELT  , DELTA ,
     3 DUSAVF, DYSAVF, ELL    , EN     , ENDTM  , ENSQ  , EPSTR , FODEN ,
     4 HG    , PRANO , PRF    , PSTAT  , PTEMP  , R     , RE    , REO   ,
     5 RHO   , RHO1  , RHOL   , RHOO   , RHOU   , RHOV  , RITE1 , RITE2 ,
     6 RITE3 , RITE4 , RPLUS  , SNSLT4, STRTTM, TB    , TBLKPL, TITLF ,
     7 TO    , TOTIME, TPLUS  , TSAT   , TT     , UBLKPL, UBJLK , JPLCL ,
     8 UPLUS , WWANT , X      , XT     , XTDEN  , XTNUM , XTPRT , YPLUS ,
     9 ZMAXTM
C
C   INTEGER COMMON NAMES
C
      COMMON    ITERNO, NBEGIN, NOBITR, NTIMES
C
C   LABELED COMMON
C
      COMMON/STATE1/STORE(50)/STATE2/UNITS,COMP,CONV
      COMMON/TRANSI/TRPT,TRC,TRA,TRY,TRU
C
C   DIMENSIONED COMMON
C
      DIMENSION    TITLF(14)
C
C   DIMENSIONED PROGRAM VARIABLES
C
      DIMENSION  ABINT(3), UBINT(3), V(3), VFRINT(3), XDEN(3), XNUM(3)
      DATA UNSAT, SAT / 6HUNSATU,6H  SATU /
      CALL  TIMEI(STRTTM)
    2 DELTA=0.0
      UPLUS=0.0
      YPLUS=0.0
      TPLUS=0.0
      XNUM(1)=0.0
      XDEN(1)=0.0
      XTNUM=0.0
      XTDEN=0.0
      CALL  SLITE (0)
      SNSLT4=0.
      UBINT(1)=0.0
      UBLKP1=0.0
      UBLKPL=0.0
      VER=0.0
      VERNUM=0.0
      ALFBAR=0.
      ABINT(1)=0.
```

```
      VERINT(1)=0.0
      MANY=0
      SATUR=0.0
      DELY=DYSAVE
      DELU=DUSAVE
      DYO2=DELY/2.0
      DYO3=DELY/3.0
      DUO3=DELU/3.0
      TODUO3=2.0*DUO3
      TBLKPL=(TO-TB)/(TO*BETA)
C
C  NEAR THE WALL, UNSATURATED
C
      IF(RITE1) 700,701,700
  701 WRITE(6,110)
      WRITE(6,116)
  700 N1=0
   30 USAVE=UPLUS
      YSAVE=YPLUS
      PTESAV=TO
      TSAVE=TPLUS
      ALFM1=ALPHA
   31 CALL PROPTY(YPLUS,TPLUS)
      DO 10 I=2,3
      CON1=RHO*ENSQ*UPLUS*YPLUS
      CONST=CON1*(1.0-EXP(-CON1/AMU))
    4 F1=DELY/(AMU+CONST)
      G1=DELY/((AK/PRANO)+(CP*CONST))
      TT=TPLUS+G1/2.0
      CALL PROPTY(YPLUS, TT )
      UU=UPLUS+F1/2.0
      YY=YPLUS+DYO2
      CON1=RHO*ENSQ*UU*YY
      CONST=CON1*(1.0-EXP(-CON1/AMU))
      F2=DELY/(AMU+CONST)
      G2=DELY/((AK/PRANO)+(CP*CONST))
      TT=TPLUS+G2/2.0
      CALL PROPTY(YPLUS, TT )
      UU=UPLUS+F2/2.0
      YY=YPLUS+DYO2
      CON1=RHO*ENSQ*UU*YY
      CONST=CON1*(1.0-EXP( -CON1/AMU))
      F3=DELY/(AMU+CONST)
      G3=DELY/((AK/PRANO)+(CP*CONST))
      TT=TPLUS+G3
      CALL PROPTY(YPLUS, TT )
      YPLUS=YPLUS+DELY
      UU=UPLUS+F3
      CON1=RHO*ENSQ*UU*YPLUS
      CONST=CON1*(1.0-EXP(-CON1/AMU))
      F4=DELY/(AMU+CONST)
      G4=DELY/((AK/PRANO)+(CP*CONST))
      UPLUS=UPLUS+((F1+F2+F2+F3+F3+F4)/6.0)
      TPLUS=TPLUS+((G1+G2+G2+G3+G3+G4)/6.0)
      CALL PROPTY(YPLUS,TPLUS)
      UBINT(I)=UPLUS*(RPLUS-YPLUS)
```

```
      VFRINT(I)=UBINT(I)*ALPHA
      ABINT(I)=VFRINT(I)/UPLUS
      XNUM(I)=ALRHO*UBINT(I)
      XDEN(I)=RHO1*UBINT(I)
   10 CONTINUE
      IF(ABS(TB-PTEMP)-0.01)61,61,63
   63 IF(TBLKPL-TPLUS)62,61,60
   61 SATUR=PTEMP
      GO TO 60
   62 YWANT=YSAVE+((TBLKPL-TSAVE)*(YPLUS-YSAVE)/(TPLUS-TSAVE))
      MANY=MANY+1
      DELY=(YWANT-YSAVE)/2.0
      DYO2=DELY/2.0
      YPLUS=YSAVE
      TPLUS=TSAVE
      PTEMP=PTESAV
      UPLUS=USAVE
      GO TO 31
   60 XTNUM=XTNUM+((XNUM(1)+4.0*XNUM(2)+XNUM(3))*DYO3)
      XTDEN=XTDEN+((XDEN(1)+4.0*XDEN(2)+XDEN(3))*DYO3)
      VFRNUM=VFRNUM+((VFRINT(1)+4.0*VFRINT(2)+VFRINT(3))*DYO3)
      ALFBAR=ALFBAR+((ABINT(1)+4.0*ABINT(2)+ABINT(3))*DYO3)
      XTPRT=XTNUM/XTDEN
      UBLKP1=UBLKP1+((UBINT(1)+4.0*UBINT(2)+UBINT(3))*DYO3)
      UBLKPL=(2.0*UBLKP1)/(RPLUS**2)
      RHOU=RHO1*UPLUS
      RE=2.0*YPLUS*UBLKPL
      IF(RITE1)600,601,600
  601 WRITE (6,103)YPLUS,UPLUS,TPLUS,UBLKPL,XTPRT,ALPHA,RHO1,RHOU,RE
  600 XNUM(1)=XNUM(3)
      XDEN(1)=XDEN(3)
      UBINT(1)=UBINT(3)
      VFRINT(1)=VFRINT(3)
      ABINT(1)=ABINT(3)
      N1=N1+1
      IF(SATUR)12,13,12
   13 IF(BNDRY-CONST/AMU)5,5,30
    5 CALL PROPTY(YPLUS,TPLUS)
      WRITE(6,3000) CONST,AMU,YPLUS,UPLUS
      TRPT=UNSAT
      TRC =CONST
      TRA =AMU
      TRY =YPLUS
      TRU =UPLUS
      RHOTR=RHO
      AMUTR=AMU
      EPSTR= 2.0*AMUTR / RHOTR
      DALDY=(ALFM1-ALPHA)/(2.0*DELY)
      GO TO 500
C
C  NEAR THE WALL     SATURATION
C
   12 DELTA=YPLUS
      DELY=DYSAVE
      DYO2=DELY/2.
      DYO3=DELY/3.
```

```
      IF(RITE2)702,703,702
  703 WRITE(6,104) DELTA
  702 N2=0
      CALL PROPTY(YPLUS,TPLUS)
   23 CONTINUE
      ALFM1=ALPHA
      DO 20 I=2,3
      CON1=RHO*ENSQ*UPLUS*YPLUS
      CONST=CON1*(1.0-EXP(-CON1/AMU))
   24 F1=DELY/(AMU+CONST)
      CALL PROPTY(YPLUS+DYO2,TPLUS)
      UU=UPLUS+F1/2.0
      YY=YPLUS+DYO2
      CON1=RHO*ENSQ*UU*YY
      CONST=CON1*(1.0-EXP(-CON1/AMU))
      F2=DELY/(AMU+CONST)
      CALL PROPTY(YPLUS+DYO2,TPLUS)
      UU=UPLUS+F2/2.0
      YY=YPLUS+DYO2
      CON1=RHO*ENSQ*UU*YY
      CONST=CON1*(1.0-EXP(-CON1/AMU))
      F3=DELY/(AMU+CONST)
      YPLUS=YPLUS+DELY
      CALL PROPTY(YPLUS,TPLUS)
      UU=UPLUS+F3
      CON1=RHO*ENSQ*UU*YPLUS
      CONST=CON1*(1.0-EXP(-CON1/AMU))
      F4=DELY/(AMU+CONST)
      UPLUS=UPLUS+((F1+F2+F2+F3+F3+F4)/6.0)
      CALL PROPTY(YPLUS,TPLUS)
      UBINT(I)=UPLUS*(RPLUS-YPLUS)
      VFRINT(I)=UBINT(I)*ALPHA
      ABINT(I)=VFRINT(I)/UPLUS
      XNUM(I)=ALRHO*UBINT(I)
      XDEN(I)=RHO1*UBINT(I)
   20 CONTINUE
      XTNUM=XTNUM+((XNUM(1)+4.0*XNUM(2)+XNUM(3))*DYO3)
      XTDEN=XTDEN+((XDEN(1)+4.0*XDEN(2)+XDEN(3))*DYO3)
      VFRNUM=VFRNUM+((VFRINT(1)+4.0*VFRINT(2)+VFRINT(3))*DYO3)
      ALFBAR=ALFBAR+((ABINT(1)+4.0*ABINT(2)+ABINT(3))*DYO3)
      XTPRT=XTNUM/XTDEN
      UBLKP1=UBLKP1+((UBINT(1)+4.0*UBINT(2)+UBINT(3))*DYO3)
      UBLKPL=(2.0*UBLKP1)/(RPLUS**2)
      RHOU=RHO1*UPLUS
      RE=2.0*YPLUS*UBLKPL
      IF(RITE2)602,603,602
  603 WRITE(6,103) YPLUS,UPLUS,TPLUS,UBLKPL,XTPRT,ALPHA,RHO1,RHOU,RE
  602 XNUM(1)=XNUM(3)
      XDEN(1)=XDEN(3)
      UBINT(1)=UBINT(3)
      VFRINT(1)=VFRINT(3)
      ABINT(1)=ABINT(3)
      N2=N2+1
      IF(BNDRY-CONST/AMU)25,25,23
   25 WRITE(6,108) CONST,AMU,YPLUS,UPLUS
      TRPT=SAT
```

```
      TRC  =CONST
      TRA  =AMU
      TRY  =YPLUS
      TRU  =UPLUS
      WRITE (6,106)
      YDIFT=2.0*DELY
      V(1)=1.0/(AMU+CONST)
      V1=V(1)
      VSTRT=V1
      VTR=V1
      P=0.0
      UBINT(3)=UPLUS*(RPLUS-YPLUS)/V1
      XNUM(3)=ALRHO*UBINT(1)
      XDEN(3)=RHO1*UBINT(1)
      AMUTR=AMU
      RHOTR=RHO
      EPSTR=2.0*AMUTR/RHOTR
      DALDY=(ALFM1-ALPHA)/(2.0*DELY)
      GO TO 441
C
C  FAR FROM THE WALL. UNSATURATED
C
  500 CONTINUE
      IF(RITE3)704,705,704
  705 WRITE(6,105) CONST
      WRITE(6,106)
  704 N3=0
      V(1)=1.0/(AMU+CONST)
      V1=V(1)
      VSTRT=V1
      VTR=V1
      P=0.0
      UBINT(1)=UPLUS*(RPLUS-YPLUS)/V1
      VERINT(1)=UBINT(1)*ALPHA
      ABINT(1)=VERINT(1)/UPLUS
      XNUM(1)=ALRHO*UBINT(1)
      XDEN(1)=RHO1*UBINT(1)
   42 VSAVE=V(1)
      PSAVE=P
      TSAVE=TPLUS
      USAVE=UPLUS
      YSAVE=YPLUS
      VSTSAV=VSTRT
      VTRSAV=VTR
   68  DO 37 K=2,3
   36 DO 34 I=2,3
   33 P1=DELU/(SQRT((1.0-AMU*VSTRT )/RHO))
      G1=DELU/(CP+(VSTRT*(AK/PRANO-CP*AMU)))
      TT=TPLUS+G1/2.0
      CALL PROPTY(YPLUS, TT )
      VEE=(VSTRT+VTR)/2.0
      P2=DELU/(SQRT((1.0-AMU*VEE)/RHO))
      G2=DELU/(CP+(VEE*(AK/PRANO-CP*AMU)))
      TT=TPLUS+G2/2.0
      CALL PROPTY(YPLUS, TT )
      P3=DELU/(SQRT((1.0-AMU*VEE)/RHO))
```

```
      G3=DELU/(CP+(VEE*(AK/PRANO-CP*AMU)))
      TT=TPLUS+G3
      CALL PROPTY(YPLUS, TT )
      P4=DELU/(SQRT((1.0-AMU*VTR)/RHO))
      G4=DELU/(CP+(VTR*(AK/PRANO-CP*AMU)))
      P1=P+((P1+P2+P2+P3+P3+P4)/6.0)
      VNEW=V1*(EXP((-CAPPA)*P1))
   35 IF((ABS(VTR-VNEW))-0.005)21,21,22
   22 VTR=VNEW
      CALL PROPTY(YPLUS,TPLUS)
      GO TO 33
   21 UPLUS=UPLUS+DELU
      P=P1
      VSTRT=VNEW
      V(I)=VNEW
      VTR=VNEW
      TPLUS=TPLUS+((G1+G2+G2+G3+G3+G4)/6.0)
      CALL PROPTY(YPLUS,TPLUS)
   34 CONTINUE
      YPLU1=YPLUS+((1.0/V(1)+4.0/V(2)+1.0/V(3))*(DUO3))
      YDIFT=YPLU1-YPLUS
      YPLUS=YPLU1
      UBINT(K)=UPLUS*(RPLUS-YPLUS)/VSTRT
      VFRINT(K)=UBINT(K)*ALPHA
      ABINT(K)=VFRINT(K)/UPLUS
      XNUM(K)=ALRHO*UBINT(K)
      XDEN(K)=RHO1*UBINT(K)
   37 V(1)=V(3)
      IF(ABS(TB-PTEMP)-0.01)64,64,65
   64 SATUR=PTEMP
      GO TO 66
   65 IF(TBLKPL-TPLUS)67,64,66
   67 UWANT=USAVE+((TBLKPL-TSAVE)*(UPLUS-USAVE)/(TPLUS-TSAVE))
      MANY=MANY+1
      DELU=(UWANT-USAVE)/4.0
      DUO3=DELU/3.
      TODUO3=2.*DUO3
      V(1)=VSAVE
      P=PSAVE
      TPLUS=TSAVE
      UPLUS=USAVE
      YPLUS=YSAVE
      VSTRT=VSTSAV
      VTR=VTRSAV
      CALL PROPTY(YPLUS, TPLUS)
      GO TO 68
   66 XTNUM=XTNUM+((XNUM(1)+4.0*XNUM(2)+XNUM(3))*(TODUO3))
      XTDEN=XTDEN+((XDEN(1)+4.0*XDEN(2)+XDEN(3))*(TODUO3))
      VFRNUM=VFRNUM+((VFRINT(1)+4.0*VFRINT(2)+VFRINT(3))*(TODUO3))
      ALFBAR=ALFBAR+((ABINT(1)+4.0*ABINT(2)+ABINT(3))*TODUO3)
      XTPRT=XTNUM/XTDEN
      UBLKP1=UBLKP1+((UBINT(1)+4.0*UBINT(2)+UBINT(3))*(TODUO3))
      UBLKPL=(2.0*UBLKP1)/(RPLUS**2)
      N3=N3+1
      RHOU=RHO1*UPLUS
      RE=2.0*YPLUS*UBLKPL
```

```
      IF(RITE3)604,605,604
  605 WRITE(6,103) YPLUS,UPLUS,TPLUS,UBLKPL,XTPRT,ALPHA,RHO1,RHOJ,RE
  604 IF(SATUR)40,442,40
  442 IF(RPLUS-YPLUS) 38 ,38 ,39
   39 XNUM(1)=XNUM(3)
      XDEN(1)=XDEN(3)
      UBINT(1)=UBINT(3)
      VFRINT(1)=VFRINT(3)
      ABINT(1)=ABINT(3)
      GO TO 42
   38 WRITE(6,106)
      CALL FINISH
      GO TO 998
C
C  AWAY FROM THE WALL    . SATURATION
C
   40 IF(RITE4) 441,707,441
  707 WRITE(6,108) SATUR
  441 CONTINUE
      DELU=DUSAVE
      DUO3=DELU/3.
      TODUO3=2.*DUO3
      N4=0
      DELTA=YPLUS
      CALL PROPTY(YPLUS,TPLUS)
      XNUM(1)=XNUM(3)
      XDEN(1)=XDEN(3)
      UBINT(1)=UBINT(3)
      VFRINT(1)=VFRINT(3)
      ABINT(1)=ABINT(3)
      YASU=YPLUS+2.0*YDIFT
      DDY=YDIFT/2.0
      PSAVE=P
      USAVE=UPLUS
      YSAVE=YPLUS
      VSAVE=VSTRT
   52 DO 43 K=2,3
  552 DO 44 I=2,3
   49 P1=DELU/(SQRT((1.0-AMU*VSTRT)/RHO) )
      CALL PROPTY(YPLUS+DDY,TPLUS)
      VEF=(VSTRT+VTR)/2.0
      P2=DELU/(SQRT(1.0-AMU*VFE)/RHO)
      CALL PROPTY(YPLUS+DDY,TPLUS)
      P3=DELU/(SQRT((1.0-AMU*VEF)/RHO) )
      CALL PROPTY(YPLUS+2.0*DDY,TPLUS)
      P4=DELU/(SQRT((1.0-AMU*VTR)/RHO) )
      P1=P+((P1+P2+P2+P3+P3+P4)/6.0)
      VNEW=V1*(EXP((-CAPPA)*P1))
   46 IF((ABS(VTR-VNEW))-0.005) 47,47,48
   48 VTR=VNEW
      CALL PROPTY(YPLUS,TPLUS)
      GO TO 49
   47 UPLUS=UPLUS+DELU
      P=P1
      VSTRT=VNEW
      V(I)=VNEW
```

```
      VTR=VNEW
      YPLUS=YPLUS+2.0*DDY
      CALL PROPTY(YPLUS,TPLUS)
   44 CONTINUE
      YPLU1=YSAVE+((1.0/V(1)+4.0/V(2)+1.0/V(3))*(DUO3))
      IF((ABS(YPLU1-YASU))-0.010)51,51,50
   50 UPLUS=USAVE
      YPLUS=YSAVE
      NNNN=NNNN+1
      IF(NNNN-50)310,999,999
  310 P=PSAVE
      YASU=YPLU1
      VSTRT=VSAVE
      DDY=(YPLU1-YSAVE)/2.0
      VTR=V(2)
      GO TO 552
   51 YPLUS=YPLU1
      YDIFT=YPLUS-YSAVE
      UBINT(K)=UPLUS*(RPLUS-YPLUS)/VSTRT
      VFRINT(K)=UBINT(K)*ALPHA
      ABINT(K)=VFRINT(K)/UPLUS
      XNUM(K)=ALRHO*UBINT(K)
      XDEN(K)=RHO1*UBINT(K)
      YASU=YPLUS+2.0*YDIFT
      DDY=YDIFT/2.0
      PSAVE=P
      NNNN=0
      USAVE=UPLUS
      YSAVE=YPLUS
      VSAVE=VSTRT
      V(1)=V(3)
   43 CONTINUE
      XTNUM=XTNUM+((XNUM(1)+4.0*XNUM(2)+XNUM(3))*(TODUO3))
      XTDEN=XTDEN+((XDEN(1)+4.0*XDEN(2)+XDEN(3))*(TODUO3))
      VFRNUM=VFRNUM+((VFRINT(1)+4.0*VFRINT(2)+VFRINT(3))*(TODUO3))
      ALFBAR=ALFBAR+((ABINT(1)+4.0*ABINT(2)+ABINT(3))*TODUO3)
      XTPRT=XTNUM/XTDEN
      UBLKP1=UBLKP1+((UBINT(1)+4.0*UBINT(2)+UBINT(3))*(TODUO3))
      UBLKPL=(2.0*UBLKP1)/(RPLUS**2)
      RHOU=RHO1*UPLUS
      RE=2.0*YPLUS*UBLKPL
      IF(RITE4)4442,607,4442
  607 WRITE(6,103) YPLUS,UPLUS,TPLUS,UBLKPL,XTPRT,ALPHA,RHO1,RHOU,RE
 4442 IF(RPLUS-YPLUS) 38 ,38 ,54
   54 XNUM(1)=XNUM(3)
      XDEN(1)=XDEN(3)
      UBINT(1)=UBINT(3)
      VFRINT(1)=VFRINT(3)
      ABINT(1)=ABINT(3)
      N4=N4+1
      GO TO 52
  999 WRITE (6,9991)NNNN
  998 CONTINUE
      CALL START
 1000 CONTINUE
      RETURN
```

```
 103 FORMAT(9G13.5)
 104 FORMAT(39H0  CLOSE TO THE WALL, SATURATED, DELTA=F12.6,10H    PTEM
    1P=F12.6)
 105 FORMAT(48H0  AWAY FROM THE WALL, NOT SATURATED,  CONST=   F12.6)
 106 FORMAT(1HL,3X,2HY+,12X,2HU+,10X,2HT+,10X,5HUBLK+,8X,8HXT(PART),
    1   6X,5HALPHA,7X,6HRHOBAR,7X,6HRHO*U+,9X,2HRE)
 108 FORMAT(33H0  AWAY FROM THE WALL, SATURATED  4G15.7)
 110 FORMAT(20HL  CLOSE TO THE WALL)
 116 FORMAT(1HL,5X,2HY+,11X,2HU+,11X,2HT+,10X,5HUBLK+,7X,8HXT(PART),
    1   6X,5HALPHA,8X,6HRHOBAR,7X,6HRHO*U+,9X,2HRE /1HL)
3000 FORMAT(71H TRANSITION POINT REACHED IN NEAR WALL UNSAT, CONST, AMU
    1, YPLUS, UPLUS= 4G15.7)
9991 FORMAT(8HL  NNNN=   I5,42H CASE CANNOT BE CONTINUED, AT EFN 50-310
    1      )
     END
```

```
$IBFTC PRPFTY
      SUBROUTINE PROPTY(Y,TEMP)
C
C  REAL COMMON NAMES
C
      COMMON    ABWANT, AK    , AKF   , AKO   , ALFBAR, ALFCL , ALPHA ,
     1 ALRHO , AMU   , AMUF  , AMUL  , AMUO  , AMUV  , BETA  , BNORY ,
     2 CAPPA , CP    , CPFCPO, CPGF  , CPO   , DALDY , DELT  , DELTA ,
     3 DUSAVE, DYSAVE, ELL   , EN    , ENDTM , ENSQ  , EPSTR , FODEN ,
     4 HG    , PRANO , PRE   , PSTAT , PTEMP , R     , RE    , REO   ,
     5 RHO   , RHO1  , RHOL  , RHOO  , RHOU  , RHOV  , RITE1 , RITE2 ,
     6 RITE3 , RITE4 , RPLUS , SNSLT4, STRTTM, TB    , TBLKPL, TITLE ,
     7 TO    , TOTIME, TPLUS , TSAT  , TT    , UBLKPL, UBULK , UPLCL ,
     8 UPLUS , WWANT , X     , XT    , XTDEN , XTNUM , XTPRT , YPLUS ,
     9 ZMAXTM
C
C  INTEGER COMMON NAMES
C
      COMMON    ITERNO, NBEGIN, NOBITR, NTIMES
C
C  LABELED COMMON
C
      COMMON/STATE1/STORE(50)/STATE2/UNITS,COMP,CONV
C
C  DIMENSIONED COMMON
C
      DIMENSION   TITLE(14)
      T = TO* (1.-BETA*TEMP)
      PTEMP=T
      STORE(7)=T
      ALPHA= 1. -(1.-ALFCL) *UPLUS/UPLCL
   11 IF (DELTA) 1,2,1
    2 CALL VISC (T,99,AMUV)
      CALL SPHT (T,99,CPV)
      CALL THCON(T,99,AKV)
      CALL STATE (3)
      V=STORE(8)
      RHOV = 1./V
      ALRHO = ALPHA * RHOV
      RHO1 = ALPHA * RHOV + (1.-ALPHA) * RHOL
      CP = CPV / CPO
      RHO = RHOV / RHOO
      AMU = AMUV / AMUO
      AK = AKV / AKO
  100 RETURN
    1 CONTINUE
      IF(SNSLT4.NE.0.) GO TO 107
  106 CALL VISC (T,AMUL,AMUV)
      CALL SLITET(1,J)
      IF(J.EQ.1) GO TO 9999
      CALL STATE (3)
```

```
      V=STORF(8)
      RHOV = 1./V
  107 ALRHO = ALPHA * RHOV
      RHO1 = ALPHA*RHOV+(1.-ALPHA) * RHOL
      AMU1 = ALPHA * AMUV + (1.-ALPHA) *AMUL
  111 RHO = RHO1 / RHOO
      AMU = AMU1 / AMUO
      SNSLT4=0.1
      RETURN
 9999 WRITE(6,200) T,PSTAT
  200 FORMAT(40H   T OR P OUT OF RANGE OF CURVE FIT   T= F15.8,2HP=F9.5)
      A = 1. / 0.
      RETURN
      END
```

```
*TWO PHASE H2 PROPERTIES, 10 ENTRY POINTS, CURVE FITS
        ENTRY    SATRT
        ENTRY    SATRP
        ENTRY    SATDEN
        ENTRY    VISC
        ENTRY    SPHT
        ENTRY    DENS
        ENTRY    THCON
        ENTRY    HOVAP
        ENTRY    CPSPG
        ENTRY    DKMU

CURFIT SXA       OUT,1
       SXA       OUT+1,2
       SXA       OUT+2,4
       ADD TWOAD
       STA RETST
       SLT 1
       TRA *+1
       SLT 2
       TRA *+1
       CLA       5,4
       STA SPHNG+4
       STA *+1
       CLA **
       SUB ONEDE
       STO TESTG
       CLA       4,4
       STA *+1
       CLA **
       SUB ONEDE

 RETST TRA **
ONEDE  DEC       99
 TESTG HTR 0
 SATRT CAL *
       TRA       CURFIT
       CLA TRYAD
       TSX WATPRT,2
       DEC 20.0            LOLIM
       DEC 180.0            UPLIM
       DEC 53.0             CHEK1
       DEC 120.2            CHEK2
       TZE NG1
       CLA       4,4
       TRA ST1+1,1
       TRA ST3
       TRA ST2
   ST1 TSX EXPON,2
```

```
       DEC 0.184307         EXPONENT 1
       DEC 22.07381         MULTIPLIER 1

       TRA OUT
   ST2 TSX EXPON,2
       DEC 0.19762          EXP 2
       DEC 20.934           MULT2
       TRA OUT
   ST3 TSX EXPON,2
       DEC 0.204194         EXP3
       DEC 20.318           MULT3
       TRA OUT
   NG1 SLN 1
       TRA OUT
 SATRP CAL *
       TRA      CURFIT
       CLA TRYAD
       TSX WATPRT,2
       DEC 38.0             LOLIM
       DEC 59.5             UPLIM
       DEC 45.0             CHEK1
       DEC 53.0             CHEK2

       TZE NG1
       CLA      4,4
       STA PROPE
       LDQ ARG
       FMP TENTH               ARG/10 IN AC
       STO      ARG
       TRA SP1+1,1
       TRA SP3
       TRA SP2
SP1    TSX      COMPE,2
       DEC 5.42572
       DEC 0.01362           MULT1
       TRA OUT
SP2    TSX      COMPF,2
       DEC 5.060184         EXP2
       DEC 0.0238            MULT2
       TRA OUT
SP3    TSX      COMPF,2
       DEC 4.8973           FXP3

       DEC 0.03106           MULT3
       TRA OUT
 TENTH DEC 0.1
SATDEN CAL *
       TRA      CURFIT
       TZE SATDG
       CLA FORAD
       TSX WATPRT,2
       DEC      20.0
       DEC 180.0            UPLIM
```

```
       DEC 56.0             CK1
       DEC 100.0            CHEK2
       DEC 130.0            CHEK3
       TZE NG1SD
       CLA     4,4
       TRA SDL1+1,1
       TRA SDL4
       TRA SDL3
       TRA SDL2

SDL1   TSX QUAD,2
       DEC 0.5744E-4
       DEC -0.01562698
       DEC 4.5995638
       TRA SATDG
SDL2   TSX QUAD,2
       DEC 0.583E-5
       DEC -0.987825E-2
       DEC 4.4395035
       TRA SATDG
SDL3   TSX QUAD,2
       DEC -7.6913E-5
       DEC 7.921E-3
       DEC 3.44626
       TRA SATDG
SDL4   TSX QUAD,2
       DEC -1.8125E-4
       DEC 4.225E-2
       DEC 0.7806

       TRA SATDG
NG1SD  SLN 1
SATDG  CLA TESTG
       TZE OUT
       CLA FORAD
       TSX WATPRT,2
       DEC     30.0
       DEC 180.0
       DEC 57.9
       DEC 100.0
       DEC 130.0
       TZE NG2
       CLA     5,4
       TRA SDG1+1,1
       TRA SDG4
       TRA SDG3
       TRA SDG2
SDG1   TSX EXPON,2
       DEC 0.9552

       DEC 0.006173
       TRA OUT
SDG2   TSX EXPON,2
```

```
        DEC 1.08091
        DEC 0.0037331
        TRA OUT
  SDG3  TSX QUAD,2
        DEC 1.0434E-5
        DEC 4.005E-3
        DEC 3.64E-2
        TRA OUT
  SDG4  TSX QUAD,2
        DEC 1.0443326E-4
        DEC -2.1051941E-2
        DEC 1.7052148
        TRA OUT
  VISC  CAL *
        TRA     CURFIT
        TZE VISGAS


        CLA ONEAD
        TSX WATPRT,2
        DEC 34.3
        DEC 59.5
        TZE NGVIL
        CLA     4,4
        TSX EXPON,2
        DEC -1.715                    EXP
        DEC 0.00429                   MULT
        TRA VISGAS
 NGVIL  SLN 1
VISGAS  CLA TESTG
        TZE OUT
        CLA FORAD
        TSX WATPRT,2
        DEC 0.0
        DEC 900.0
        DEC 90.0
        DEC 200.0


        DEC 400.0
        TZE NG2
        CLA     5,4
        STA MULTC
        STA MULTC+2
        TRA VISG1+1,1
        TRA VISG4
        TRA VISG3
        TRA VISG2
 VISG1  TSX QUAD,2
        DEC -4.296E-4
        DEC 0.22244
        DEC -0.43984
        TRA MULTC
 VISG2  TSX QUAD,2
        DEC -1.5322E-4
        DEC 0.174627
```

```
        DEC 1.5531
        TRA MULTC


VISG3   TSX QUAD,2
        DEC -1.3264E-4
        DEC 0.17608582
        DEC 0.38855739
        TRA MULTC
VISG4   TSX QUAD,2
        DEC -0.3103E-4
        DEC 0.10913939
        DEC 10.909091
MULTC   LDQ **
        FMP MULT
        STO **
        TRA OUT
MULT    DEC 1.0E-7
SPHT    CAL *
        TRA     CURFIT
        TZE SPHTG
        CLA FORAD
        TSX WATPRT,2


        DEC 25.0                 LOLIM
        DEC 59.5                 UPLIM
        DEC 50.0                 CK
        DEC 57.0                 CHK2
        DEC 59.0                 CHK3
        TZE NGSHL
        CLA     4,4
        TRA SPHT1+1,1
        TRA SPHT4
        TRA SPHT3
        TRA SPHT2
SPHT1   TSX QUART,2
        DEC 7.5936508E-6         A1
        DEC -0.10883175E-2       B1
        DEC 0.059070159          C1
        DEC -1.35463492          D1
        DEC 12.85571428          F1
        TRA SPHTG
SPHT2   TSX QUART,2


        DEC 0.5257143E-2
        DEC -1.112914286
        DEC 88.33594286
        DEC -3115.386286
        DEC 41190.32
        TRA SPHTG
SPHT3   TSX LINE,2
        DEC 4.37427
        DEC -242.08193
        TRA SPHTG
```

```
SPHT4 TSX LINE,2
      DEC 8.0                MULTIPLIER
      DEC -456.0             CONSTANT
      TRA SPHTG
NGSHL SLN 1
SPHTG CLA TESTG
      TZE OUT
      CLA FIVAD
      TSX WATPRT,2

SVNTY DEC 70.0
      DEC 1100.00            UPLIM
      DEC 175.0              CK1
      DEC 270.0
      DEC 400.0              CK3
      DEC 700.0              CK4
      TZE SPHNG
      CLA     5,4
      TRA SPTG1+1,1
      TRA SPTG5
      TRA SPTG4
      TRA SPTG3
      TRA SPTG2
SPTG1 TSX QUAD,2
      DEC 7.031E-5
      DEC -1.1437E-2
      DEC 2.949976
      TRA OUT
SPTG2 TSX QUAD,2

      DEC -9.719E-5
      DEC 5.11979E-2
      DEC -2.8972835
      TRA OUT
SPTG3 TSX QUAD,2
      DEC -8.951049E-6
      DEC 0.4994406E-2
      DEC 3.18940559
      TRA OUT
SPTG4 TSX QUAD,2
      DEC 4.6E-6
      DEC -5.93E-3
      DEC 5.398
      TRA OUT
SPTG5 TSX QUAD,2
      DEC 3.4090909E-8
      DEC -7.38636363E-5
      DEC 3.5130
      TRA OUT

SPHNG CLA ARG
      FSB SVNTY                     T-70
      TPL NG2
```

```
       CLA 2PT48
       STO **
       TRA OUT
 2PT48 DEC 2.48
  DENS CAL *
       TRA      CURFIT
       CLA TWOAD
       TSX WATPRT,2
       DEC 38.0
       DEC 59.0
       DEC 54.0
       TZE NG1
       CLA      4,4
       TRA DF1+1,1
       TRA DE2
   DE1 STA DEPRP

 DENSL LDQ ARG
       FMP C1
       FAD ONE                   ARG
       STO      POWER
       CALL     FXP3(POWER,ONTRD)

       XCA
       FMP C2
       FAD C3
       LDQ ARG
       STO ARG
       FMP C4
       FAD ARG
 DEPRP STO **
       TRA OUT

    C1 DEC -0.01684
    C2 DEC 3.0360
    C3 DEC 2.6482
    C4 DEC -0.01222
 ONTRD DEC 0.333333333
   DE2 TSX QUAD,2
       DEC -2.807925E-2
       DEC 2.992247
       DEC -76.402464
       TRA OUT
 THCON CAL *
       TRA      CURFIT
       TZE TCGAS
       CLA ONFAD
       TSX WATPRT,2
       DEC 30.0
       DEC 56.0
```

```
       TZE NGTCL
       CLA     4,4

       TSX LINE,2
       DEC 0.2075E-6
       DEC 1.15056E-5
       TRA TCGAS
NGTCL  SLN 1
TCGAS  CLA TESTG
       TZE OUT
       CLA FIVAD
       TSX WATPRT,2
       DEC 0.
       DEC 1000.0
       DEC 84.0
       DEC 227.0
       DEC 450.0
       DEC 700.0
       TZE NG2
       CLA     5,4
       STA TCMUL
       STA TCMUL+2

       TRA TGPT1+1,1
       TRA TGPT5
       TRA TGPT4
       TRA TGPT3
       TRA TGPT2
TGPT1  TSX LINE,2
       DEC 6.06667E-3
       DEC 2.533E-2
       TRA TCMUL
TGPT2  TSX QUAD,2
       DEC 1.015E-5
       DEC 4.44473E-3
       DEC 8.5215E-2
       TRA TCMUL
TGPT3  TSX QUAD,2
       DEC -8.3E-6
       DEC 1.0344E-2
       DEC -0.31248
       TRA TCMUL

TGPT4  TSX QUAD,2
       DEC 7.0E-7
       DEC 2.86E-3
       DEC 1.23
       TRA TCMUL
TGPT5  TSX LINE,2
       DEC 3.91E-3
       DEC 0.84
TCMUL  LDQ **
       FMP TENM5
```

```
      STO **
      TRA OUT
TENM5 DEC 1.0E-5
HOVAP CAL *
      TRA     CURFIT
      CLA TRYAD
      TSX WATPRT,2
      DEC 20.0
      DEC 180.0
      DEC 110.0
      DEC 155.0
      TZE NG1
      CLA     4,4
      TRA HOV1+1,1
      TRA HOV3
      TRA HOV2
 HOV1 TSX LINE,2
      DEC -0.62575
      DEC 200.285
      TRA OUT
 HOV2 TSX QUAD,2
      DEC -5.388E-3
      DEC 0.52816
      DEC 137.275
      TRA OUT
 HOV3 TSX QUAD,2
      DEC -4.176865E-2
      DEC 12.084423
      DEC -782.79038
      TRA OUT
CPSPG CAL *
      TRA     CURFIT
      CLA FIVAD
      TSX WATPRT,2
      DEC 45.0
      DEC 59.5
      DEC 51.0
      DEC 55.0
      DEC 56.0
      DEC 56.5
      TZE NG1
      CLA     4,4
      TRA CPSP1+1,1
      TRA CPSP5
      TRA CPSP4
      TRA CPSP3
      TRA CPSP2
CPSP1 TSX QUAD,2
      DEC 0.0199
      DEC -1.664667
```

```
       DEC 38.26
       TRA OUT
CPSP2  TSX QUAD,2
       DEC 0.08595238
       DEC -8.5936905
       DEC 219.80911
       TRA OUT
CPSP3  TSX QUAD,2
       DEC 0.379464
       DEC -40.220536
       DEC 1071.4139
       TRA OUT
CPSP4  TSX LINE,2
       DEC 7.774
       DEC -426.281
       TRA OUT


CPSP5  TSX LINE,2
       DEC 2.6
       DEC -133.95
       TRA OUT
 DKMU  CAL *                         THE 1ST ARGUMENT(RHO) IN THE CALLING
       TRA     CURFIT
       TZE MUDIF                     (U-U*) IS COMPUTED.    LN RHO WILL
       CLA FORAD                     BE IN THE P_ACE OF RHO.
       TSX WATPRT,2
       DEC 0.062
       DEC 6.24
       DEC 0.156
       DEC 0.437
       DEC 0.936
       TZE NGK
       CLA     4,4
       STA KMUL
       STA KMUL+2
       TRA KDIF1+1,1


       TRA KDIF4
       TRA KDIF3
       TRA KDIF2
KDIF1  TSX LINE,2
       DEC 0.47365
       DEC 0.04368
       TRA KMUL
KDIF2  TSX LINE,2
       DEC 0.36953
       DEC 0.06048
       TRA KMUL
KDIF3  TSX LINE,2
       DEC 0.32561
       DEC 0.07795
       TRA KMUL
KDIF4  TSX QUAD,2
       DEC 0.0178
```

```
      DEC 0.2747
      DEC 0.111

 KMUL LDQ **
      FMP TENM5
      STO **
      TRA MUDIF
  NGK SLN 1
MUDIF CLA TESTG
      TZE OUT
      CLA FORAD
      TSX WATPRT,2
      DEC 0.062
      DEC 4.87
      DEC 0.75
      DEC 2.18
      DEC 3.06
      TZE NG2
      CALL     ALOG(ARG)

      LXA      OUT+2,4
      STO ARG
      CLA      5,4
      TRA DMU1+1,1
      TRA DMU4
      TRA DMU3
      TRA DMU2
 DMU1 TSX LINE,2
      DEC 1.50406
      DEC -15.17481
      TRA LNDMU                        LN(U-U*) IN ADDRESS OF 3,4
 DMU2 TSX QUAD,2
      DEC 0.056307
      DEC 1.65504
      DEC -15.1357
      TRA LNDMU
 DMU3 TSX QUAD,2
      DEC -0.46503

      DEC 2.94351
      DEC -15.82432
      TRA LNDMU
 DMU4 TSX QUAD,2
      DEC 6.0983251
      DEC -12.400227
      DEC -6.8734401
LNDMU STO      POWER
      CALL     EXP(POWER)
```

```
        LXA      OUT+2,4
        STO*       5,4
        TRA OUT
    ONE DEC 1.0
 WATPRT PAX 0,1                       N TO INDEX 1
        ADD TWOAD                     N+2

        STA RETRN+1
        CLA*       3,4
        STO ARG
        CAS 1,2                      LOLIM
        TRA *+3                     OK
        TRA PT1                      LOLIM = ARG
        TRA GOBAK                    LOLIM GREATER THAN +RG
        CAS 2,2                      UPLIM
        TRA GOBAK                    ARG GREATER THAN UPLIM
        TRA *+1                      OK
        TNX PT1,1,1                  UK  TEST IN  IF N=1 GO TO PT1
        CAS 3,2                      TEST BR1  N=M-1
        TRA *+3                      BR1 LESS THAN ARG
        TRA PT1                      BR1 =
        TRA PT1                         GREATER THAN ARG
        TNX PT2,1,1                  IF N-1=1 THEN N-2  ARG IN PT2
        CAS 4,2                      TEST BR2  N=N-2
        TRA *+3
        TRA PT2

        TRA PT2
        TNX PT3,1,1
        CAS 5,2                       TEST BR3  N=N-3
        TRA *+3
        TRA PT3
        TRA PT3
        TNX PT4,1,1
        CAS 6,2                      TEST BR4  N=N-4
        TRA PT5
        TRA PT4
        TRA PT4
  GOBAK CLA ZERO
        TRA RETRN
    PT5 CLA FIVAD
        TRA RETRN
    PT4 CLA FORAD
        TRA RETRN
    PT3 CLA TRYAD
        TRA RETRN

    PT2 CLA TWOAD
        TRA RETRN
    PT1 CLA ONEAD
```

```
 RETRN PAX 0,1
       TRA 1,2
 ONFAD DEC 1
 TWOAD DEC 2
 TRYAD DEC 3
 FORAD DEC 4
 FIVAD DEC 5
  ZERO HTR 0
   NG2 SLN 2
OUT    AXT      **,1
       AXT      **,2
       AXT      **,4
       TRA      1,4
 QUAD  STA PROQD
 COMQD LDQ ARG
       FMP 1,2                 AT


       FAD 2,2                 AT+B
       XCA
       FMP ARG                 (AT+B)T
       FAD 3,2
 PROQD STO **
       TRA 4,2
  LINE STA PROLN
 COMLN LDQ ARG
       FMP 1,2                 MX
       FAD 2,2                 MX+B
 PROLN STO **
       TRA 3,2
 QUART STA PROTC
 COORT LDQ 1,2                 A
       FMP ARG                 AT
       FAD 2,2                 AT+B
       XCA
       FMP ARG                 (AT+B)T
       FAD 3,2                 +C


       XCA
       FMP ARG                 ((AT+B)T+C)T
       FAD 4,2                 +D
       XCA
       FMP ARG
       FAD 5,2                 +E
 PROTC STO **
       TRA 6,2
 EXPON STA PROPE
COMPE  CLA      1,2
       STO      POWER
       CALL     FXP3(ARG,POWER)
```

```
        LXA     OUT+2,4
        XCA

        FMP 2,2                 MULTPLIER
  PROPF STO **
        TRA 3,2
POWER   PZE
    ARG HTR 0
        *LDIR

        END
```

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TABLE I. - INPUT AND OUTPUT RESULTS OF ANALYTICAL PROGRAM FOR LOW-PRESSURE HYDROGEN FILM-BOILING MIST FLOW AND COMPARISON WITH EXPERIMENTAL DATA[a]

(a) U.S. Customary units.

Run number	Input								Output					Experiment			
Run number	Length from inlet, in.	Wall temperature, T_o, °R	Bulk temperature, T_b, °R	Temperature difference, ΔT, °R	Quality, x	Desired mean volume fraction vapor x, $\bar{\alpha}_w$	Desired mass flow rate, $\dot{w}_w$, ft/sec	Bulk velocity, u_b, ft/sec	Heat-transfer parameter, β	Mean volume fraction vapor, $\bar{\alpha}$	Mass flow rate, $\dot{w}$, lb/sec	Analytical heat flux, $q_{o,anal}$, Btu/(in.²)(sec)	Analytical heat-transfer coefficient, $h_{o,anal}$, Btu/(in.²)(sec)(°F)	Experimental heat-flux, $q_{o,exp}$, Btu/(in.²)(sec)	Experimental heat-transfer coefficient, h_{exp}, Btu/(in.²)(sec)(°F)	Reynolds number, Re_o	Heat flux ratio, $q_{o,cal}/q_{o,exp}$
1802	7.4	256.1	43.9	212.2	0.055	0.523	0.177	158.5	0.05744	0.525	0.1771	0.1789	0.00084	0.235	0.00111	33164	0.76
1802	8.4	252.7	43.7	209.0	.062	.5592	.177	170.6	.0710	.5612	.1764	.1850	.00086	.235	.00113	36004	.76
1805	7.4	246.8	39.8	207.0	.164	.8627	.063	162.2	.05970	.8644	.0628	.1035	.00050	.231	.00112	22468	.45
2001	9.4	414.5	45.1	369.4	.119	.6842	.170	219.2	.1216	.6860	.1706	.8003	.00217	.597	.00162	23870	1.34
2002	7.4	421.8	44.5	377.3	.140	.7389	.136	204.2	.1266	.7385	.1354	.7312	.00194	.603	.00160	20480	1.21
2002	8.4	419.2	44.2	375.0	.166	.7809	.136	234.4	.1193	.7810	.1354	.7231	.00193	.603	.00161	23195	1.20
2003	9.4	422.6	42.2	380.4	.323	.9175	.094	335.9	.1107	.9179	.0944	.6755	.00178	.606	.00159	26336	1.12
2003	10.4	419.5	41.8	377.7	.356	.9314	.094	381.9	.1057	.9314	.0936	.6627	.00175	.606	.00161	28902	1.09
2203	2.9	675.2	44.8	630.4	.240	.8401	.068	148.4	.1663	.8383	.0680	.7664	.00122	.927	.00147	7121	.83
2203	4.4	678.0	44.5	633.5	.355	.9048	.068	210.0	.1483	.9054	.0683	.8268	.00131	.927	.00146	9757	.90
2203	5.9	681.2	44.2	637.0	.468	.9410	.068	276.6	.1389	.9416	.0683	.9130	.00143	.927	.00146	12292	.98
2203	7.4	677.6	43.7	633.9	.581	.9639	.068	353.0	.1311	.9643	.0682	.9758	.00154	.927	.00146	15033	1.05
2203	8.4	676.4	43.3	633.1	.656	.9748	.068	411.4	.1268	.9751	.0683	1.0088	.00159	.927	.00147	16807	1.08
2203	9.4	674.7	42.9	631.8	.724	.9826	.068	472.9	.1230	.9825	.0678	1.0267	.00163	.927	.00147	18430	1.11
2208	1.4	681.3	----	-----	----	-----	----	-----	-----	-----	-----	------	------	----	------	-----	----

(b) SI units.

Run number	Input								Output					Experimental			
Run number	Length from inlet, cm	Wall temperature, T_o, °K	Bulk temperature, T_b, °K	Temperature difference, ΔT, °K	Quality, x	Desired mean volume fraction vapor x, $\bar{\alpha}_w$	Desired mass flow rate, $\dot{w}_w$, kg/sec	Bulk velocity, u_b, m/sec	Heat-transfer parameter, β	Mean volume fraction vapor, $\bar{\alpha}$	Mass flow rate, $\dot{w}$, kg/sec	Analytical heat flux, $q_{o,anal}$, J/(cm²)(sec)	Analytical heat-transfer coefficient, $h_{o,anal}$, J/(cm²)(sec)(°K)	Experimental heat flux, $q_{o,exp}$, J/(cm²)(sec)	Experimental heat-transfer coefficient, h_{exp}, J/(cm²)(sec)(°K)	Reynolds number, Re_o	Heat flux ratio, $q_{o,cal}/q_{o,exp}$
1802	18.8	142	24.4	118	0.055	0.523	0.0804	52.0	0.05744	0.525	0.0803	0.116	0.00098	0.152	0.00130	33164	0.76
1802	21.3	141	24.3	116	.062	.5592	.0804	55.8	.0710	.5612	.0800	.120	.00100	.152	.00132	36004	.76
1805	18.8	137	22.1	115	.064	.8627	.0286	53.2	.05970	.8644	.0285	.671	.000584	.150	.00131	22468	.45
2001	23.8	231	25.1	205	.119	.6842	.0772	71.8	.1216	.6860	.0774	.519	.00253	.387	.00189	23870	1.34
2002	18.8	235	24.7	210	.140	.7389	.0618	66.9	.1266	.7385	.0614	.474	.00226	.391	.00187	20480	1.21
2002	21.3	233	24.6	208	.166	.7809	.0618	76.9	.1193	.7810	.0614	.469	.00225	.391	.00188	23195	1.20
2003	23.8	235	23.4	211	.323	.9175	.0427	110.0	.1107	.9179	.0428	.438	.00208	.393	.00186	26336	1.12
2003	26.4	233	23.2	210	.356	.9314	.0427	125.3	.1057	.9314	.0425	.430	.00204	.393	.00188	28902	1.09
2003	7.3	375	24.9	350	.240	.8401	.0309	48.7	.1663	.8383	.0308	.497	.00142	.601	.00171	7121	.83
2003	11.2	377	24.7	352	.355	.9048	.0309	68.9	.1483	.9054	.0310	.536	.00153	.601	.00170	9757	.90
2003	14.9	378	24.6	354	.468	.9410	.0309	90.8	.1389	.9416	.0310	.592	.00167	.601	.00170	12292	.98
2003	18.8	377	24.3	352	.581	.9639	.0309	115.8	.1311	.9643	.0309	.632	.00180	.601	.00170	15033	1.05
2003	21.3	376	24.1	352	.656	.9748	.0309	135.0	.1268	.9751	.0310	.654	.00186	.601	.00171	16807	1.08
2003	23.8	375	23.8	351	.724	.9826	.0309	155.0	.1230	.9825	.0308	.666	.00189	.601	.00171	18430	1.11
2008	3.5	379	----	---	----	-----	-----	-----	-----	-----	-----	----	------	-----	------	-----	----

[a]Experimental data from ref. 1.

TABLE II. - EFFECT OF DROPLET DISTRIBUTION PROFILE ON HEAT TRANSFER

[Profile is expressed as $\alpha_l/\alpha_{l,CL} = (y/r)^{1/m}$]

Heat flux	m						Velocity profile (eq. (5a))
	2	5	7	10	20	1000	
	[a]Run 2002						
q_{anal}, Btu/(sec)(in.^{2}) (J/cm^2-sec)	0.56 (0.363)	0.614 (0.398)	0.628 (0.407)	0.642 (0.416)	0.689 (0.448)	0.686 (0.444)	0.648 (0.420)
q_{anal}/q_{exp}	.93	1.016	1.04	1.06	1.14	1.135	1.072
	[a]Run 2003						
q_{anal}, Btu/(sec)(in.^{2}) (J/cm^2-sec)	1.055 (0.684)	1.190 (0.771)	0.999 (0.648)	1.114 (0.738)	1.003 (0.650)	0.988 (0.640)	0.988 (0.640)
q_{anal}/q_{exp}	1.137	1.284	1.077	1.20	1.08	1.065	1.065

[a]See table I.

TABLE III. - COMPARISON OF QUALITIES CALCULATED FROM ANALYTICAL PROGRAM WITH THOSE BASED UPON EQUILIBRIUM-HOMOGENEOUS MODEL

Pressure, P_X		Wall temperature, T_o		Radius, R, in.		Mass flow rate, $\dot{w}$		Mean volume fraction, $\overline{\alpha}$	Equilibrium quality, x_{eq}	Analytical quality, x_{anal}	Equilibrium minus analytical quality, $x_{eq} - x_{anal}$
psia	N/cm^2	^oR	^oK	in.	cm	lb/sec	kg/sec				
100	68.9	680	378	0.25	0.635	0.1	0.0454	0.975	0.857	0.813	0.044
								.944	.72	.665	.055
								.807	.492	.366	.126
								.468	.1195	.113	.0065
140	96.5	680	378	0.25	0.635	0.18	0.0816	0.937	0.804	0.705	0.099
								.789	.506	.444	.062
								.625	.313	.288	.025
170	117	500	278	0.1675	0.426	0.14	0.0635	0.764	0.599	0.507	0.092
								.591	.398	.346	.052
								.406	.239	.231	.008

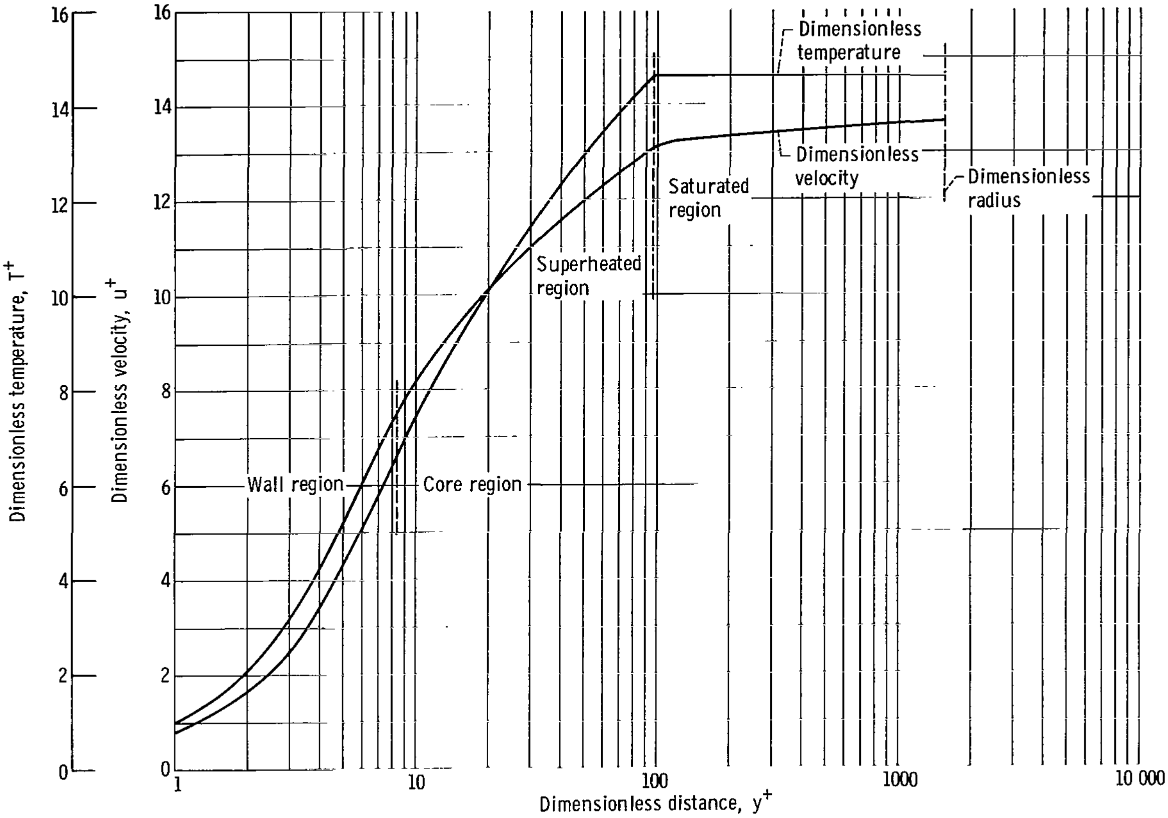


Figure 1. - Typical plot of dimensionless velocity and temperature as function of dimensionless distance. Run 1802; length from inlet, 8.44 inch (21.4 cm)(data from ref. 1).

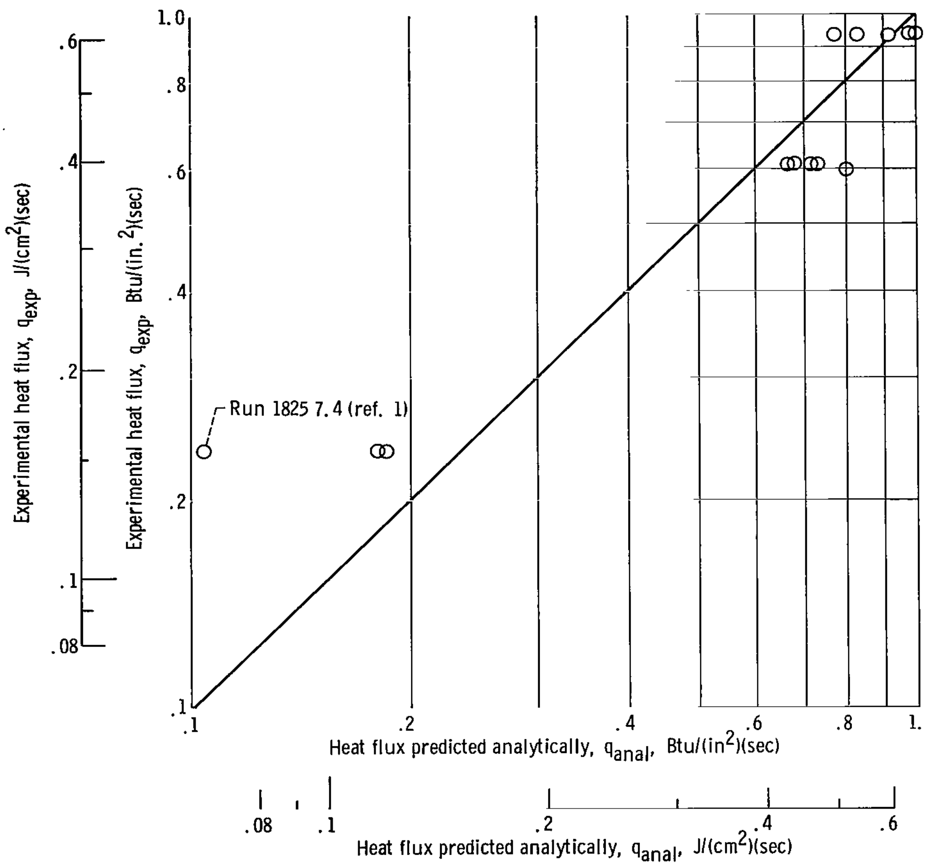


Figure 2. - Comparison of heat flux predicted for analytical program with experimental data from reference 1. Pressure, 45 pounds per square inch absolute (31 N/cm^2).

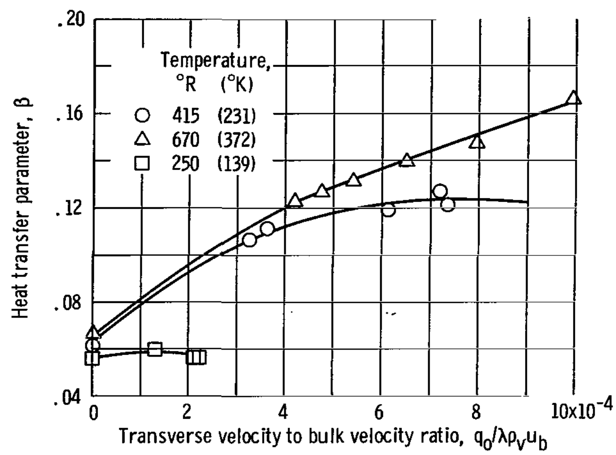


Figure 3. - Variation of heat-transfer parameter as function of transverse velocity to bulk velocity ratio. (Data from ref. 1.)

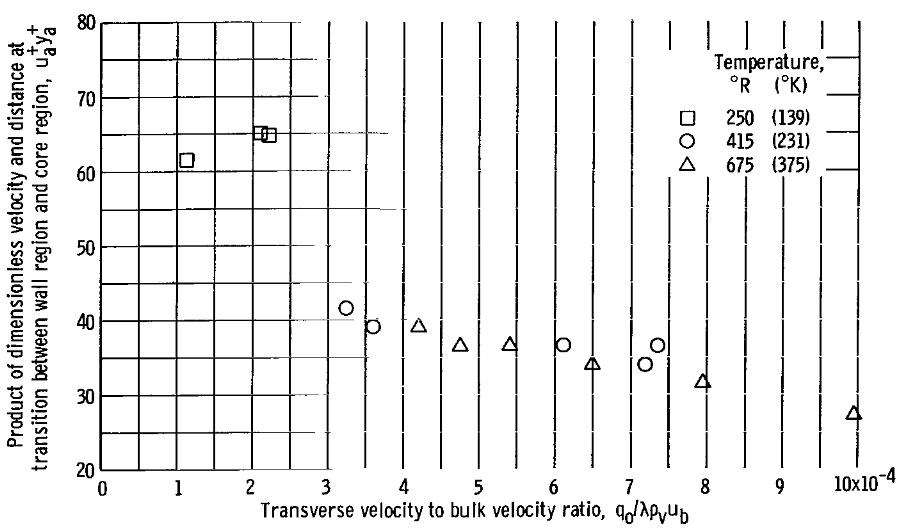
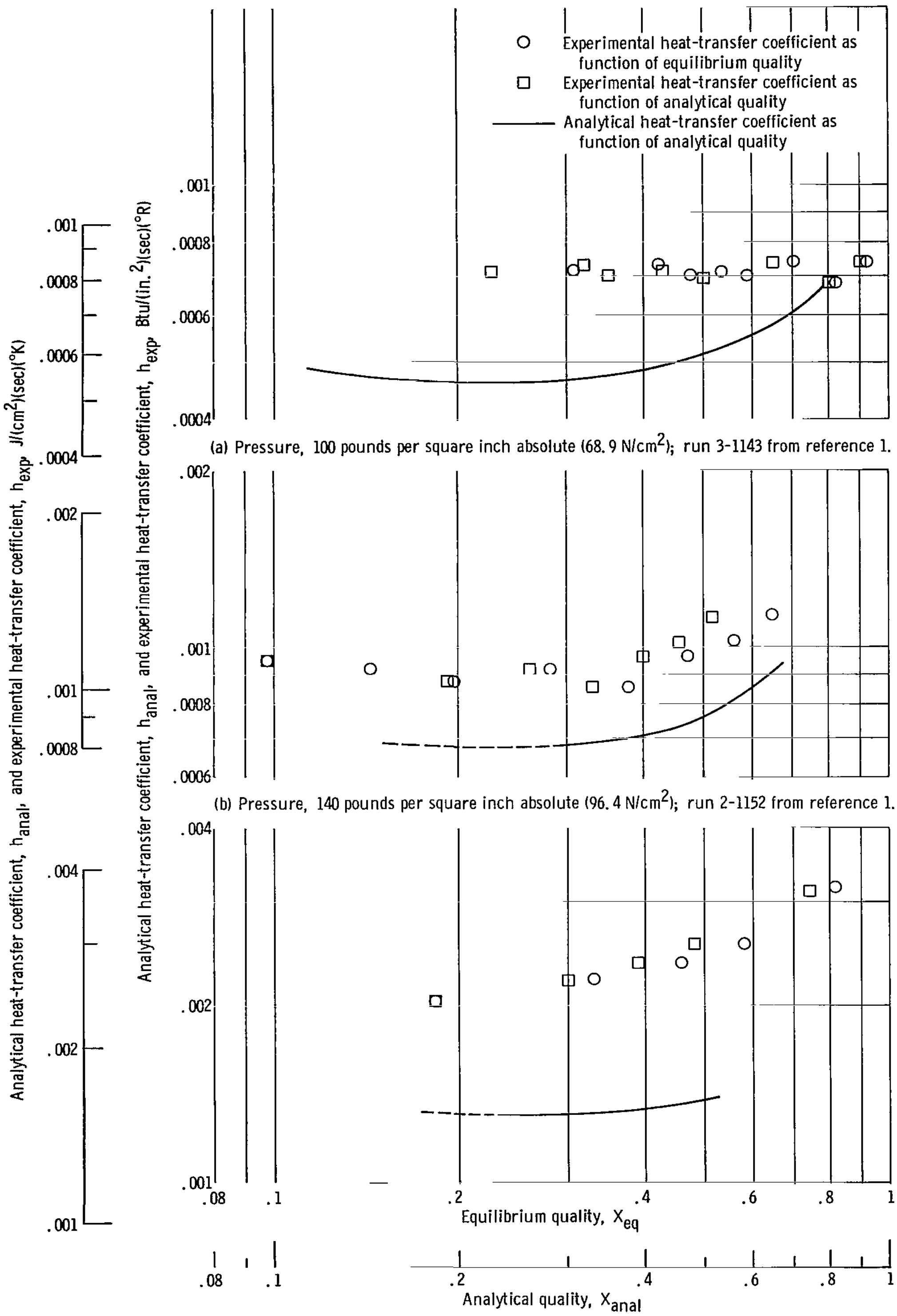


Figure 4. - Variation of product of dimensionless velocity and dimensionless distance at transition from wall to core region as function of ratio of transverse velocity to bulk velocity.



(a) Pressure, 100 pounds per square inch absolute (68.9 N/cm^2); run 3-1143 from reference 1.

(b) Pressure, 140 pounds per square inch absolute (96.4 N/cm^2); run 2-1152 from reference 1.

(c) Pressure, 170 pounds per square inch absolute (117 N/cm^2); run 8-203 from reference 1.

Figure 5. - Comparison of experimental and analytical heat-transfer coefficients as function of quality.

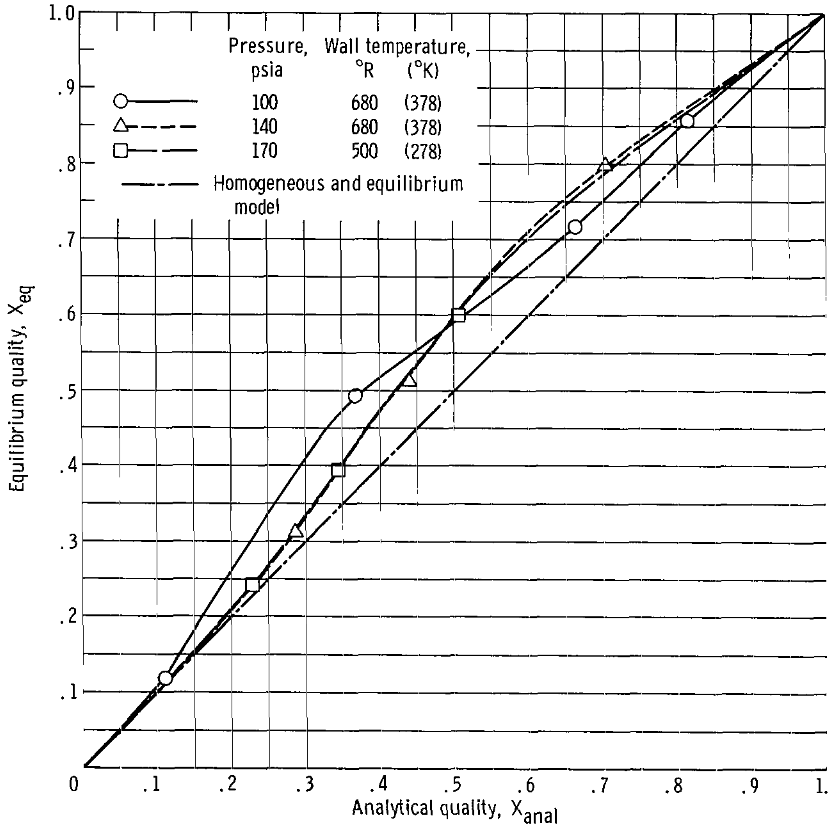


Figure 6. - Comparison of quality calculated from the analytical program with the quality based upon equilibrium-homogeneous model.

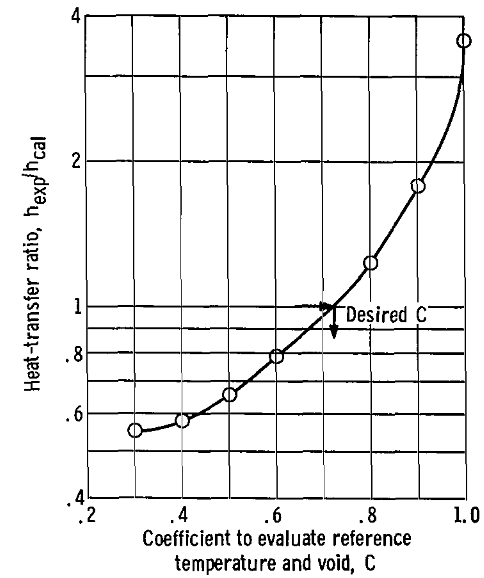


Figure 7. - Typical plot of ratio of experimental heat-transfer coefficient to corresponding value calculated from Dittus-Boelter equation using film properties evaluated at film temperature and film void given by coefficient C. Length from inlet, 7.4 in. (18.8 cm); run 2203 from reference 1.

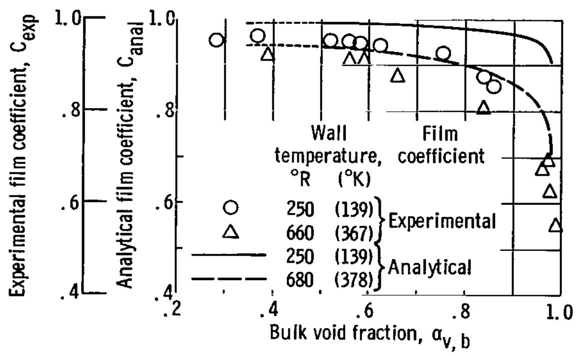


Figure 8. - Comparison of analytical and experimental values of film coefficient as functions of bulk void at various temperatures. Pressure, 45 psia (31 N/cm^2); mass flow rate, 0.1 pound per second (0.045 Kg/sec); radius, 0.1565 inch (0.398 cm).

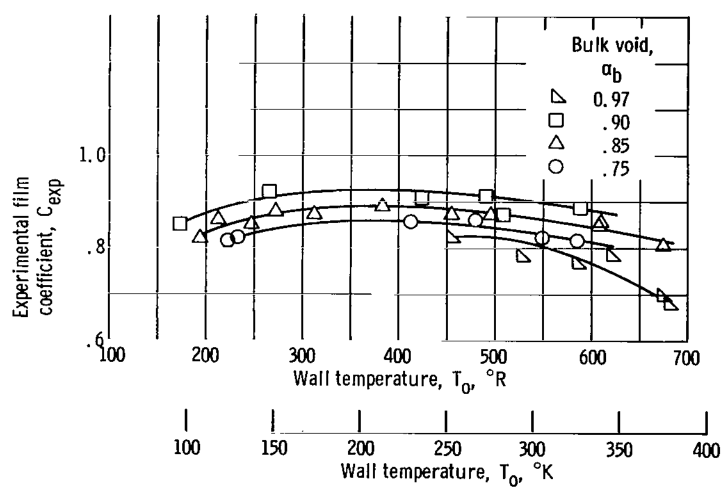


Figure 9. - Effect of wall temperature on experimental film coefficient at various bulk void. (Data from ref. 1.)

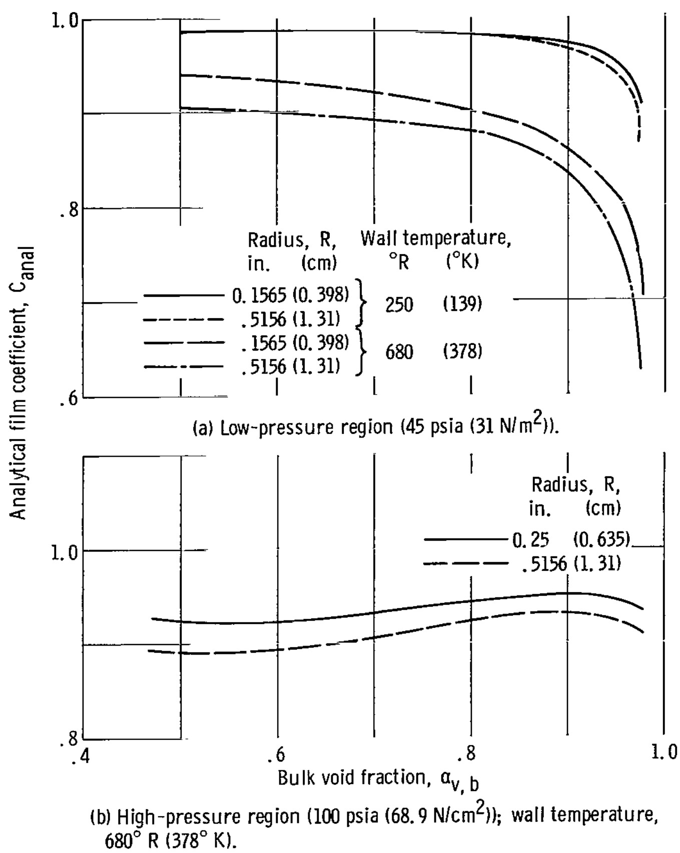


Figure 10. - Effect of tube radius on analytical film coefficient. Mass flow rate, 0.1 pound per second (0.045 Kg/sec).

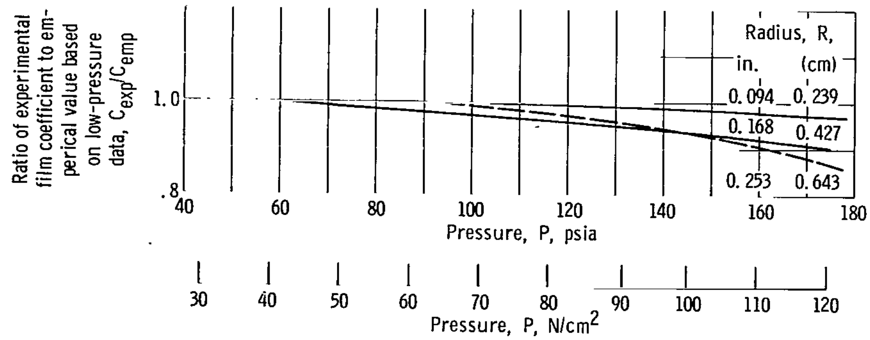


Figure 11. - Effect of tube radius and pressure on experimental film coefficient. (Data from ref. 1.)

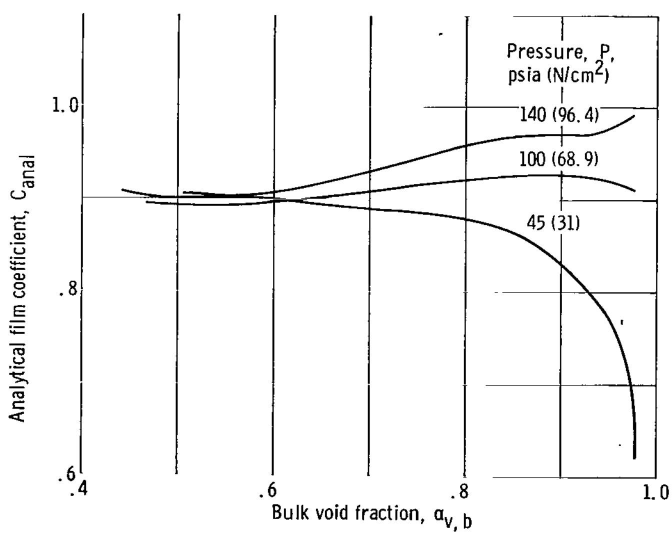


Figure 12. - Effect of pressure on analytical film coefficient. Wall temperature, 680° R (378° K); mass flow rate, 0.1 pound per second (0.45 kg/sec); radius, 0.5156 inch (1.31 cm).

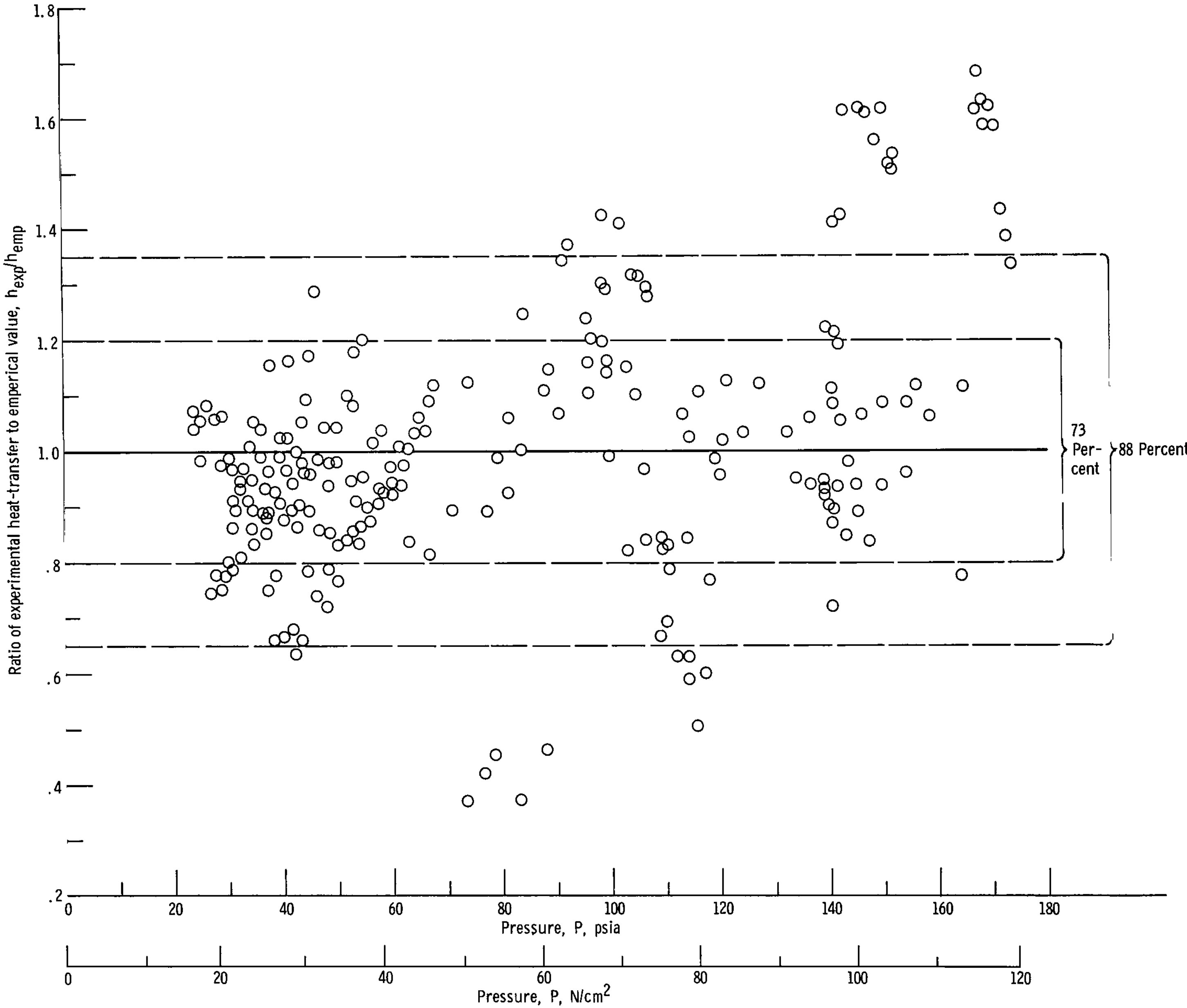


Figure 13. - Comparison of experimental and emperical heat-transfer coefficients using film coefficient based on emperical correlation of equation 37.

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